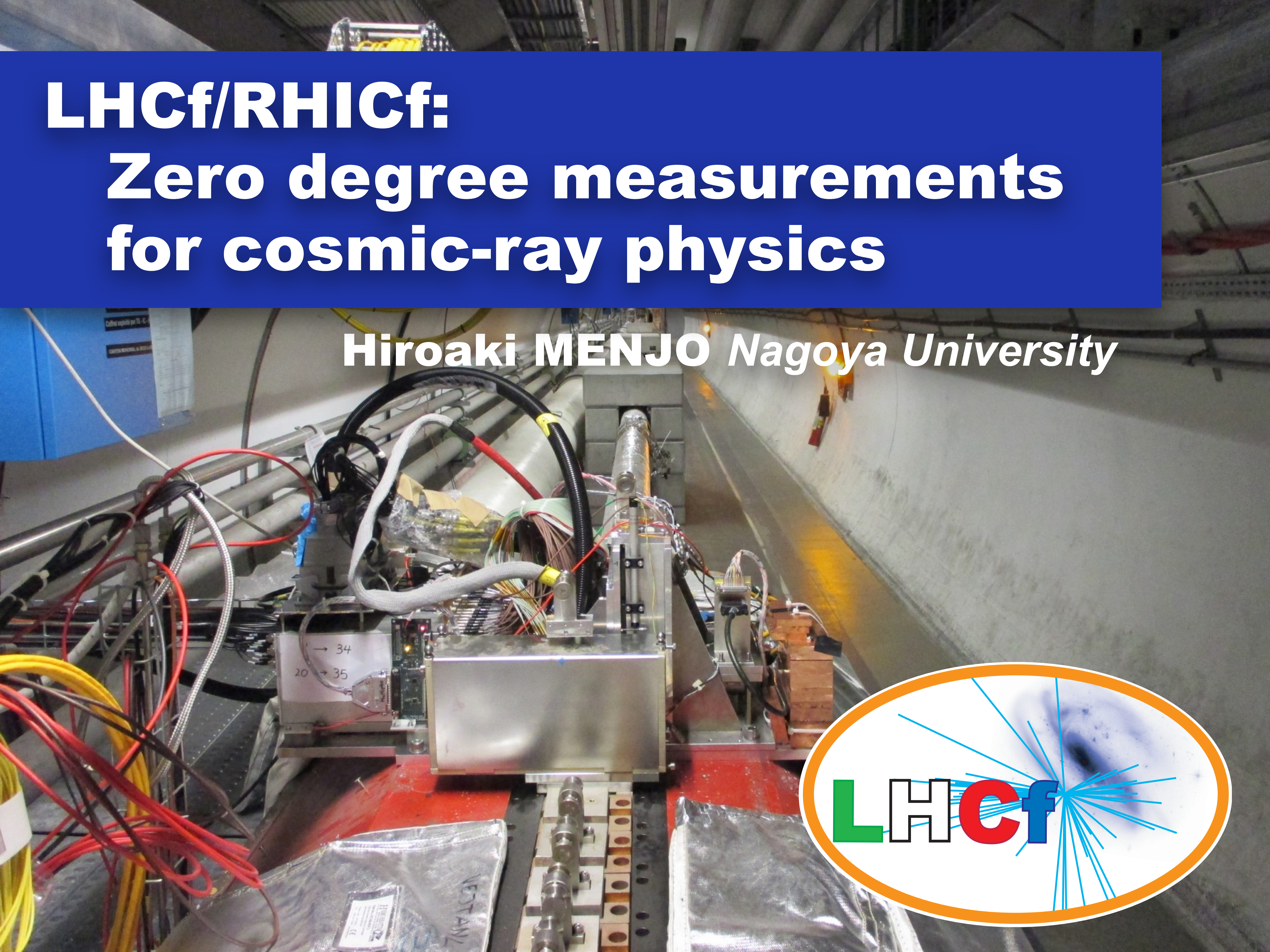
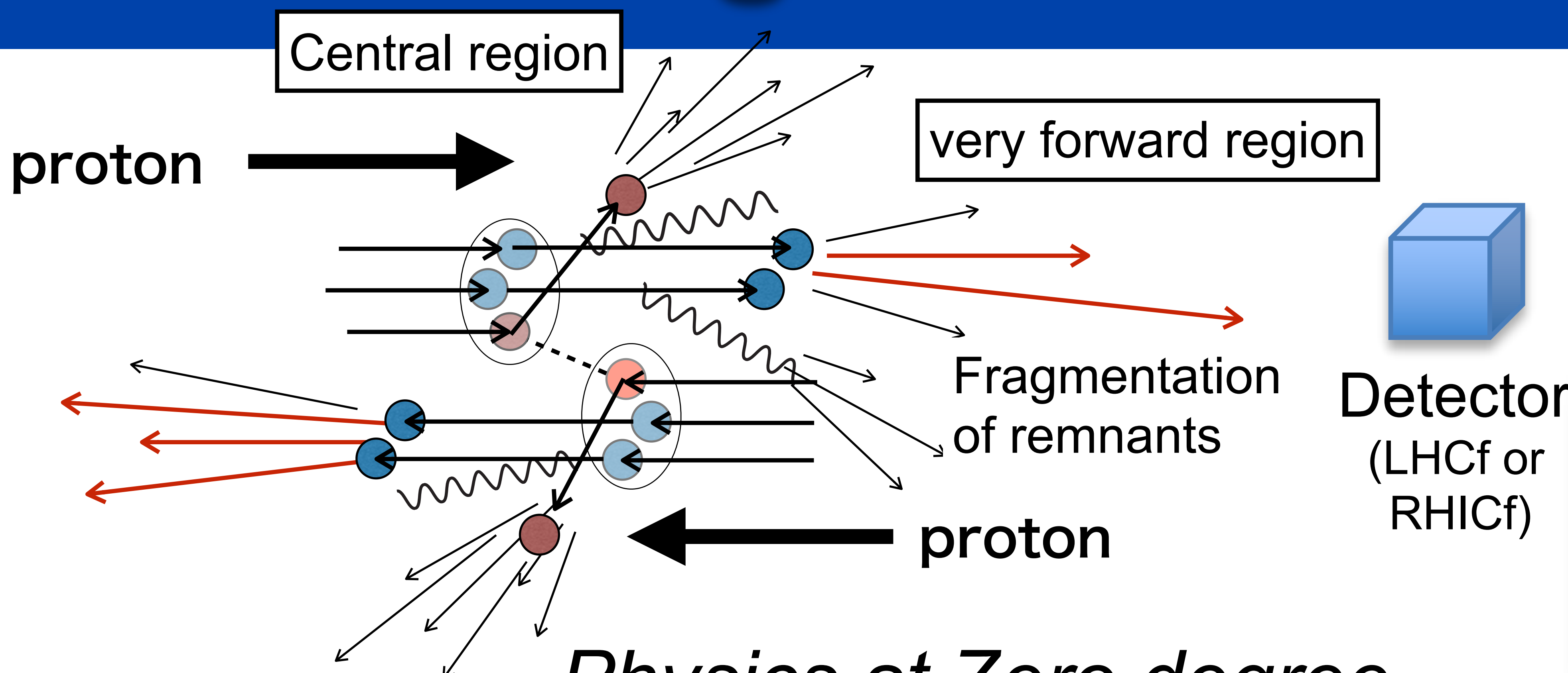
LHCf/RHICf: Zero degree measurements for cosmic-ray physics

Hiroaki MENJO *Nagoya University*



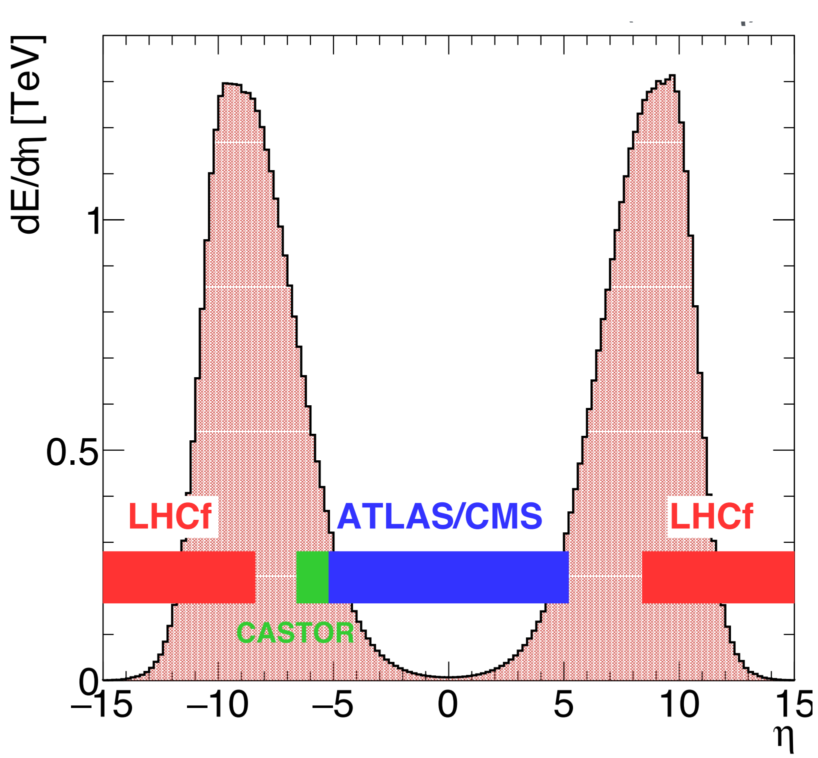
Zero-degree of collisions



Physics at Zero degree

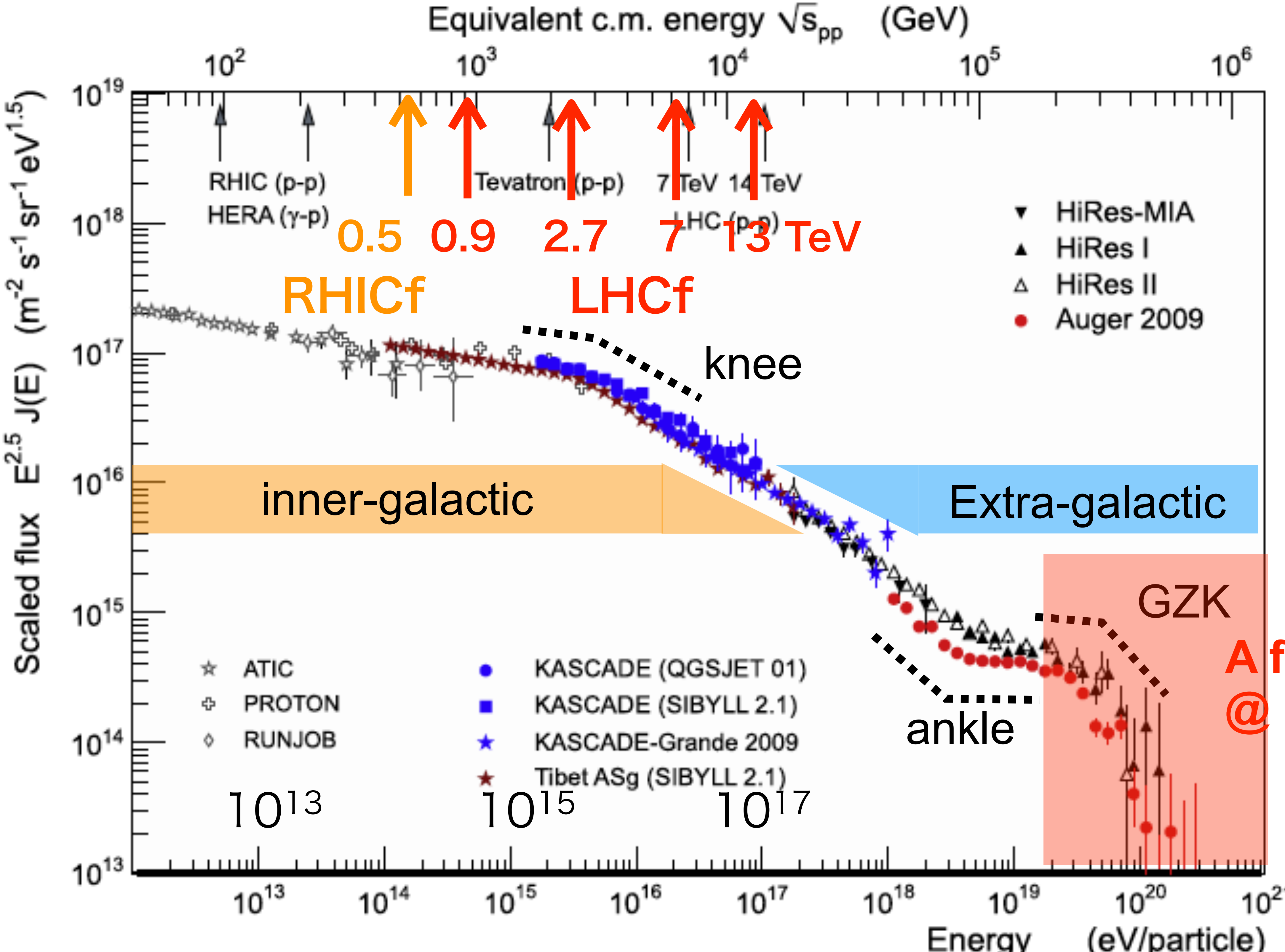
✓Soft collisions, low-pT < 1GeV
→ non-pQCD regime.
→ Phenomenological model is needed

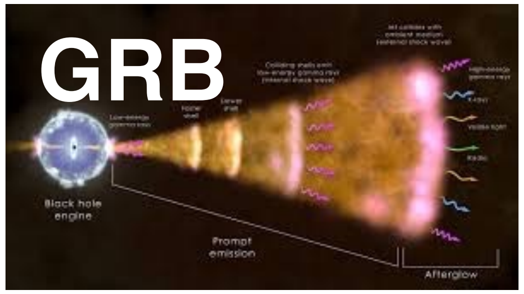
✓High energy flux
→ Most of longitudinal momentum is carried by remnants of collisions.



These are important for cosmic-ray physics, especially observation of ultra-high energy cosmic-rays

Cosmic-rays





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A few degrees @ 10^{19}eV proton

UHECR Astronomy

D'Enterria et al., 2011

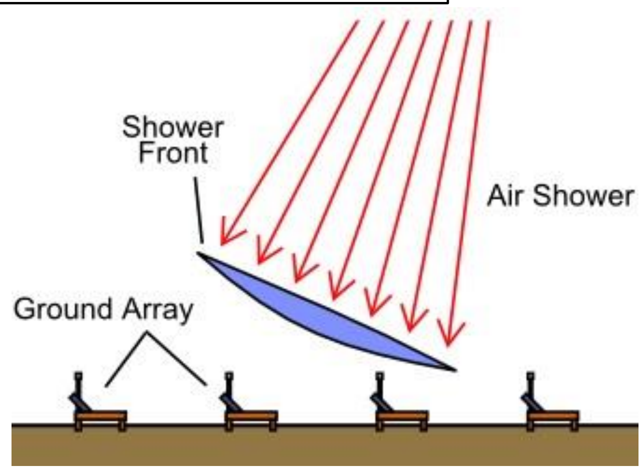
UHECR observations

Indirect observation by using the air shower technique

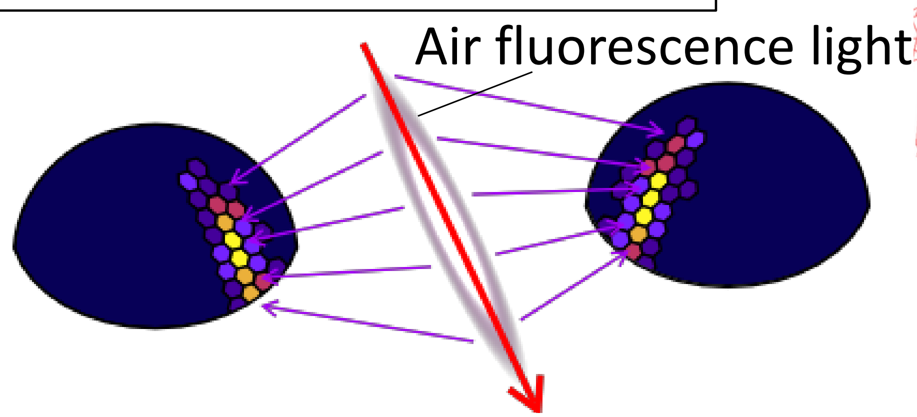
- 😊 Easy to have a large acceptance
- 😔 Uncertainty in the reconstruction of primary CR information.

- Energy spectrum
- Anisotropy
- Chemical composition

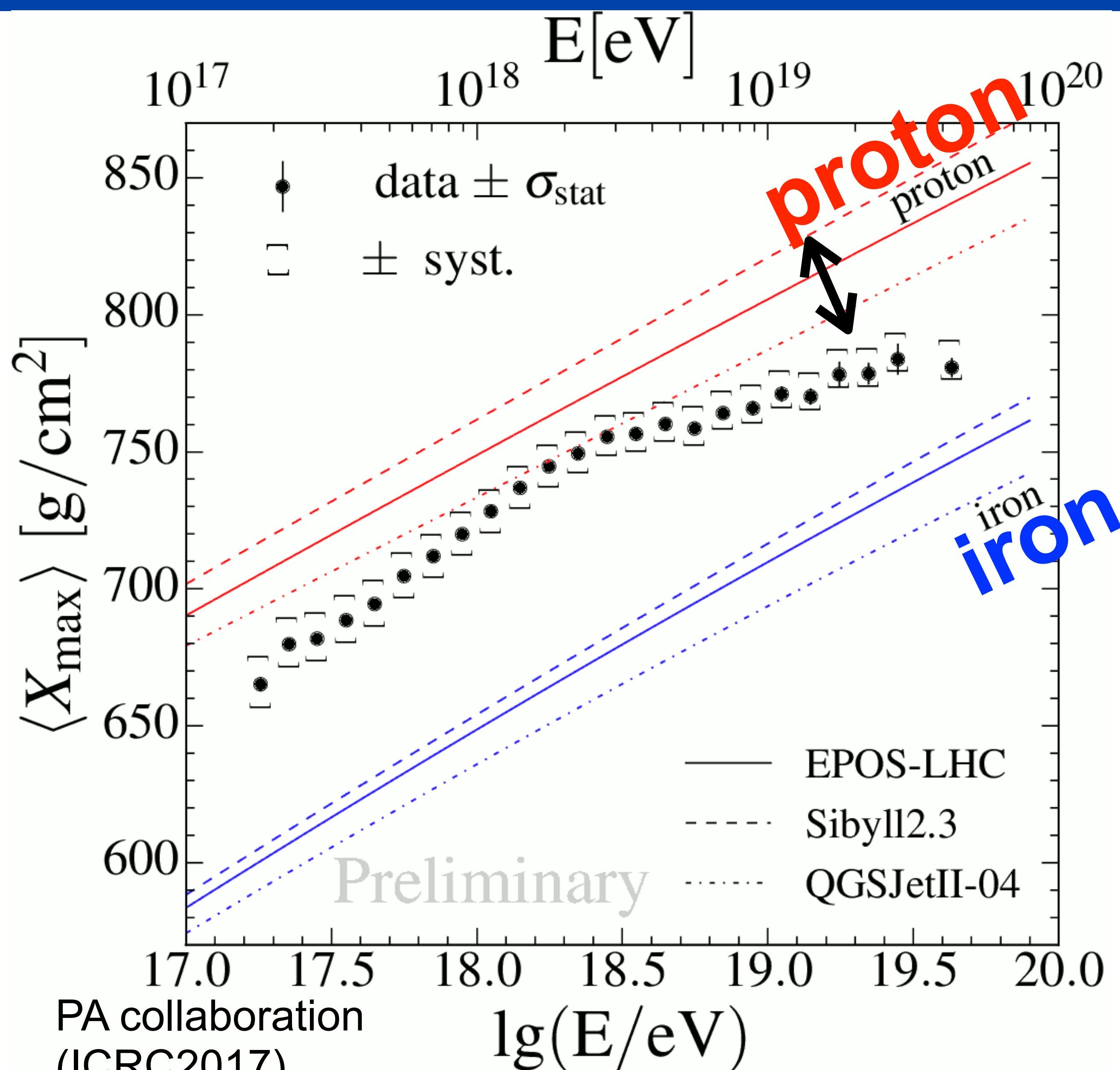
Surface detector (SD)



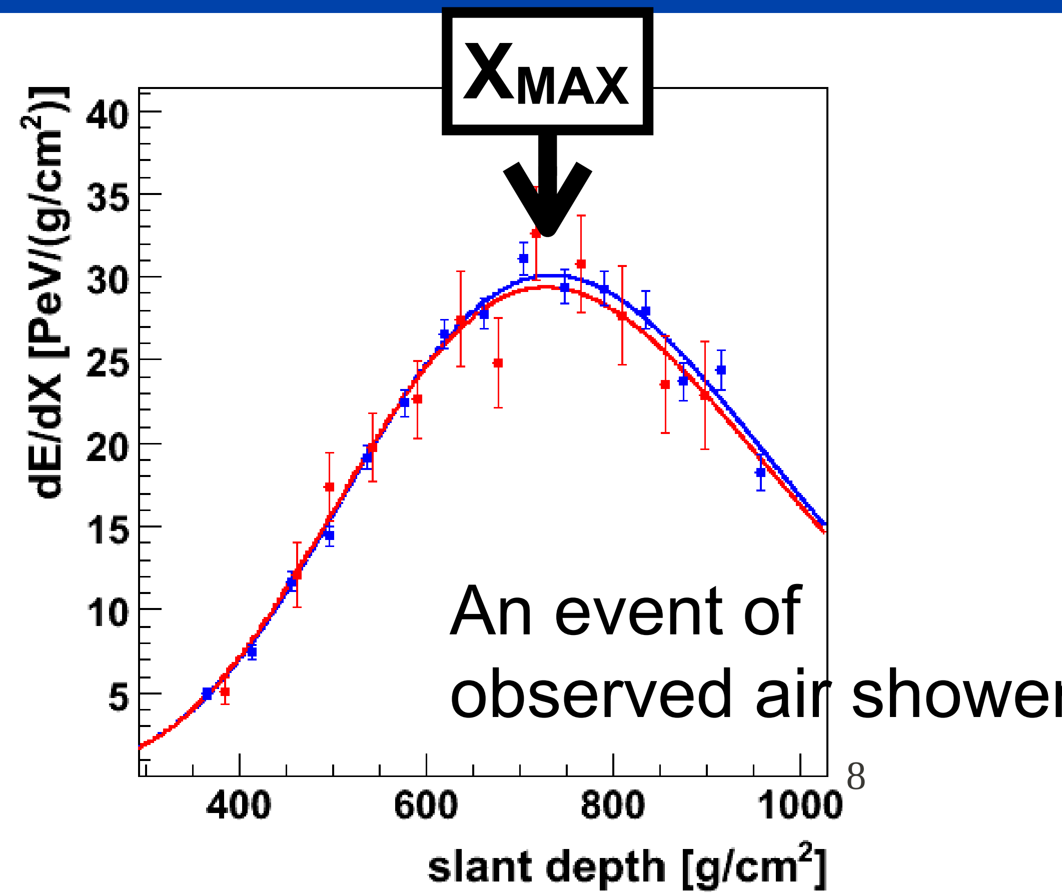
Fluorescence detector (FD)



Composition measurement



PA collaboration
(ICRC2017)



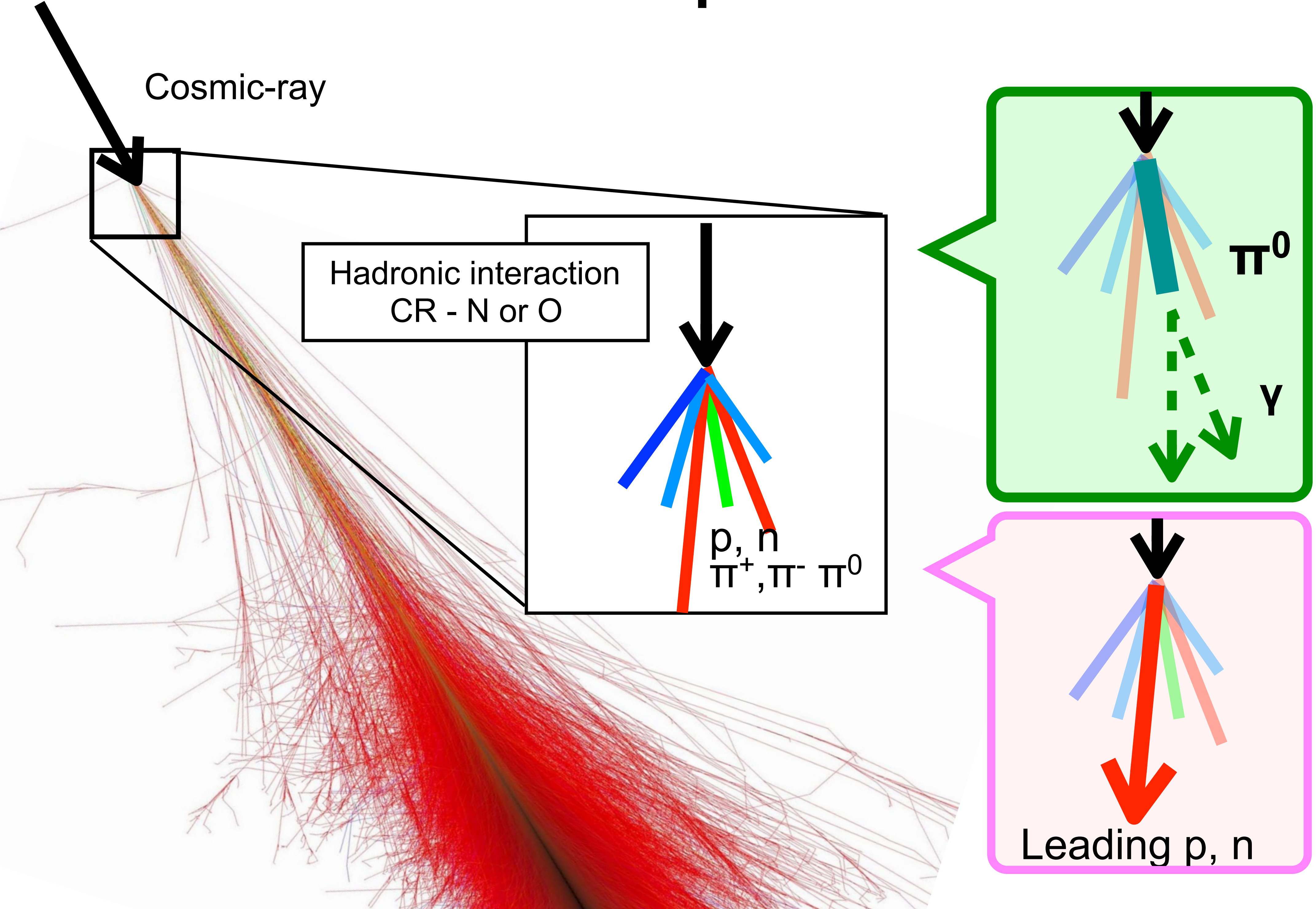
Uncertainty of hadron interaction models

V

Error of <X_{max}> measurement

- ✓ **Improvement of hadronic interaction models is one of the keys for UHECR studies.**
- ✓ **LHC provide unique opportunities to verify the models at $\sqrt{s}$=14TeV (E_{CR}=10^{17}eV)**

Air shower developments and hadronic interaction



Neutral pions

- $\pi^0 \rightarrow 2\gamma$
- Induce electromagnetic showers which is dominant components of the shower.

Leading baryons

- bring the energy to next collisions
- Inelasticity: fraction of energy used for particle productions
  $k = 1 - E_{leading}/E_{CR}$

They must be measured experimentally

We do them at LHC and RHIC

These energetic π^0 and n are always emitted into the very forward region.

The LHCf Collaboration

Y. Itow, Y. Matsubara, H. Menjo, Y. Muraki,
K. Sato, K. Ohashi, M. Ueno *(Nagoya Univ.)* T. Sako *(Univ. Tokyo)*
K. Kasahara, K. Yoshida *(Shibaura Tech.)* N. Sakurai *(Tokushima Univ.)*
S. Torii *(Waseda Univ.)* K. Shimizu, T. Tamura *(Kanagawa univ.)*
M. Haguenauer *(PolyTech)* W.C. Turner *(Bereley)*
O. Adriani, E. Berti, L. Bonechi, M. Bongi, G. Castellini,
R.D'Alessandro, P. Papini, S. Ricciarini, A. Tiberio *(INFN Florence)*
A. Trocomi *(INFN Catania)*

The RHICf Collaboration

Y. Itow, H. Menjo, K. Sato, M. Ueno *(Nagoya Univ.)*
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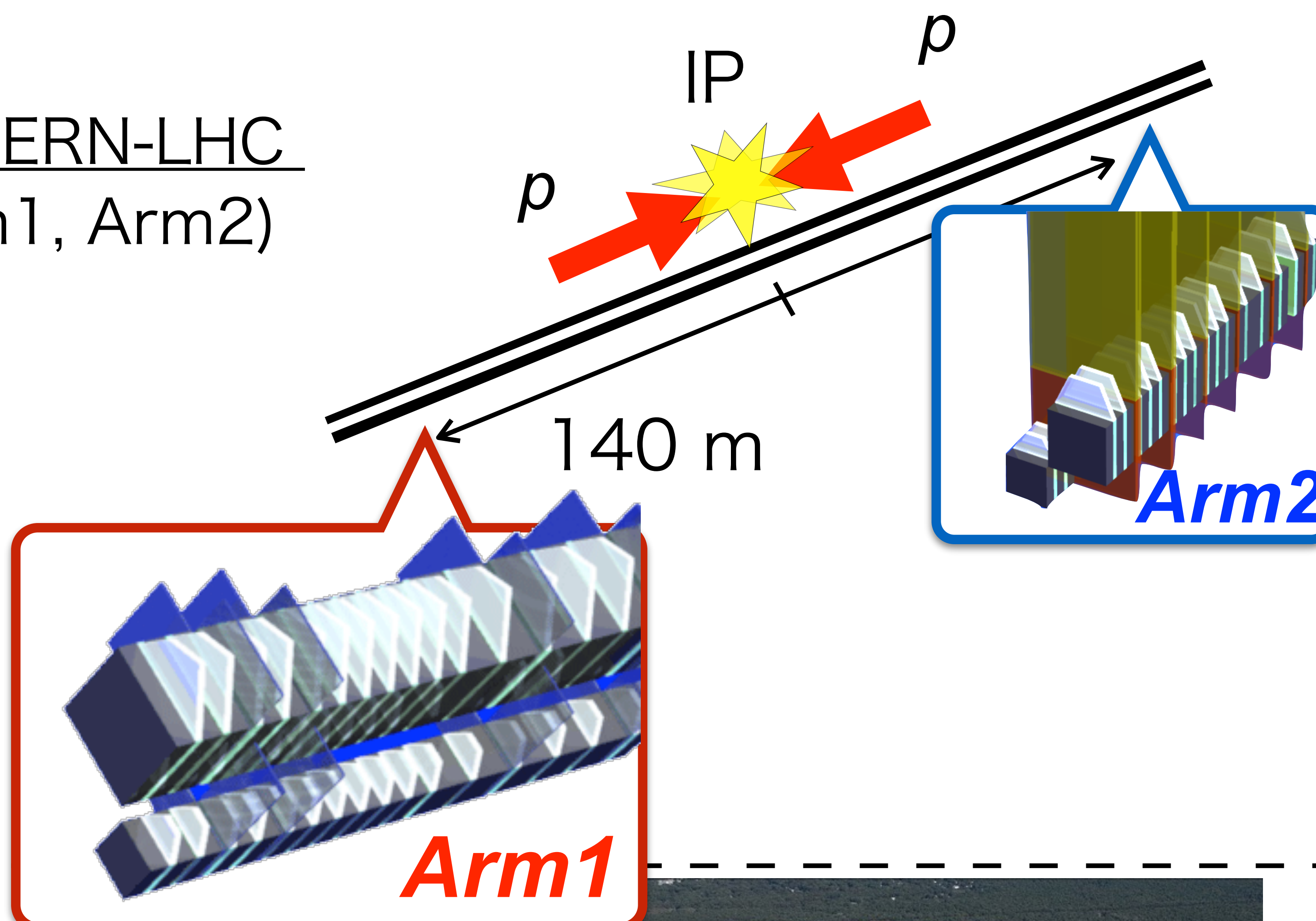
K. Kasahara, S. Torii *(Waseda Univ.)*
Y. Goto, I. Nakagawa, R. Seidl *(RIKEN)* K. Tanida *(JAEA)*
J. S. Park *(Seoul univ.)* B. Hong, M. H. Kim *(Korea univ.)*
O. Adriani, E. Berti, L. Bonechi, R.D'Alessandro *(INFN Florence)*
A. Trocomi *(INFN Catania)*

LHCf and RHICf experiments

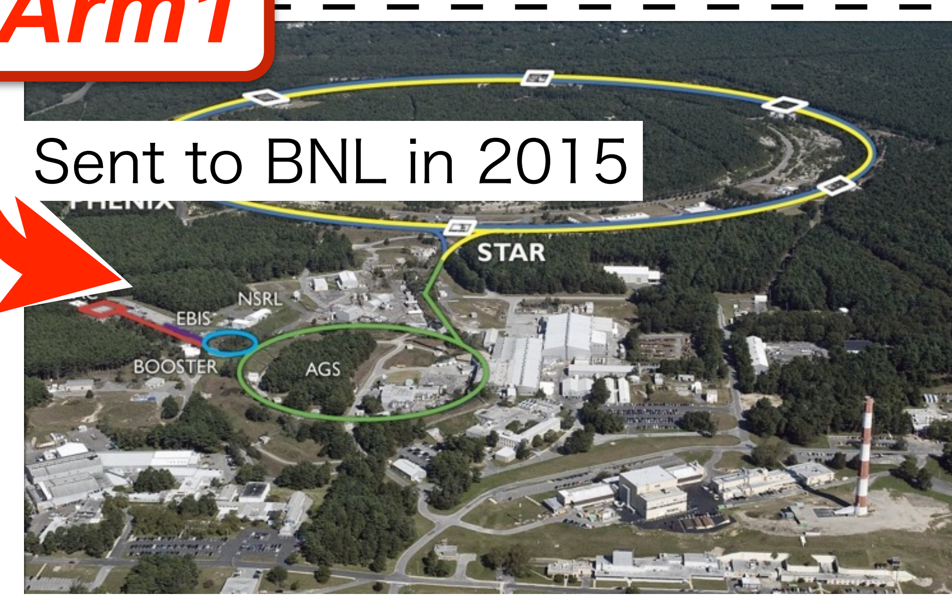
LHCf experiment

- Zero degree measurement at CERN-LHC
- Two calorimeter detectors (Arm1, Arm2) at ± 140 m from ATLAS IP
- Operations
  - pp: $\sqrt{s}$ = 0.9 TeV (2010),
    $\sqrt{s}$ = 2.76 TeV (2013),
    $\sqrt{s}$ = 7 TeV (2010),
    $\sqrt{s}$ = 13 TeV (2015)
  - pPb: $\sqrt{s_{NN}}$ = 5 TeV (2013,2016)
    $\sqrt{s_{NN}}$ = 5 TeV (2016)

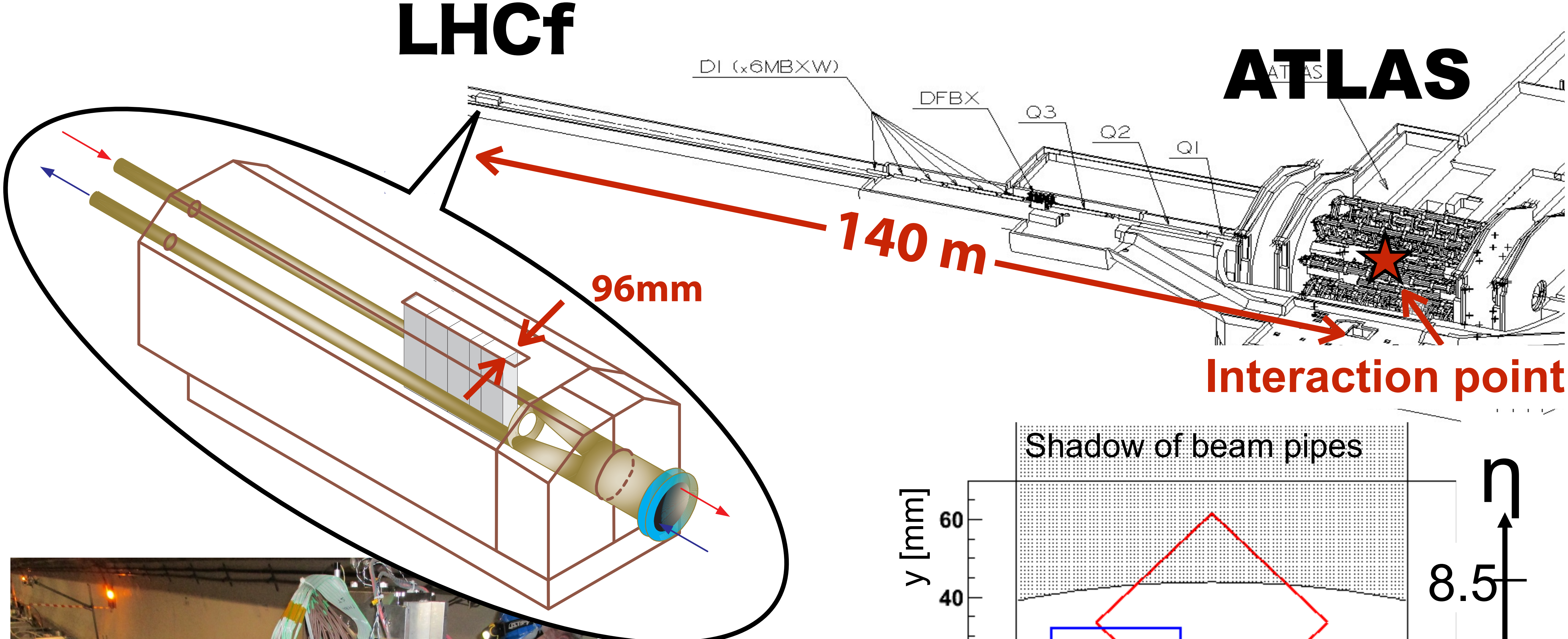


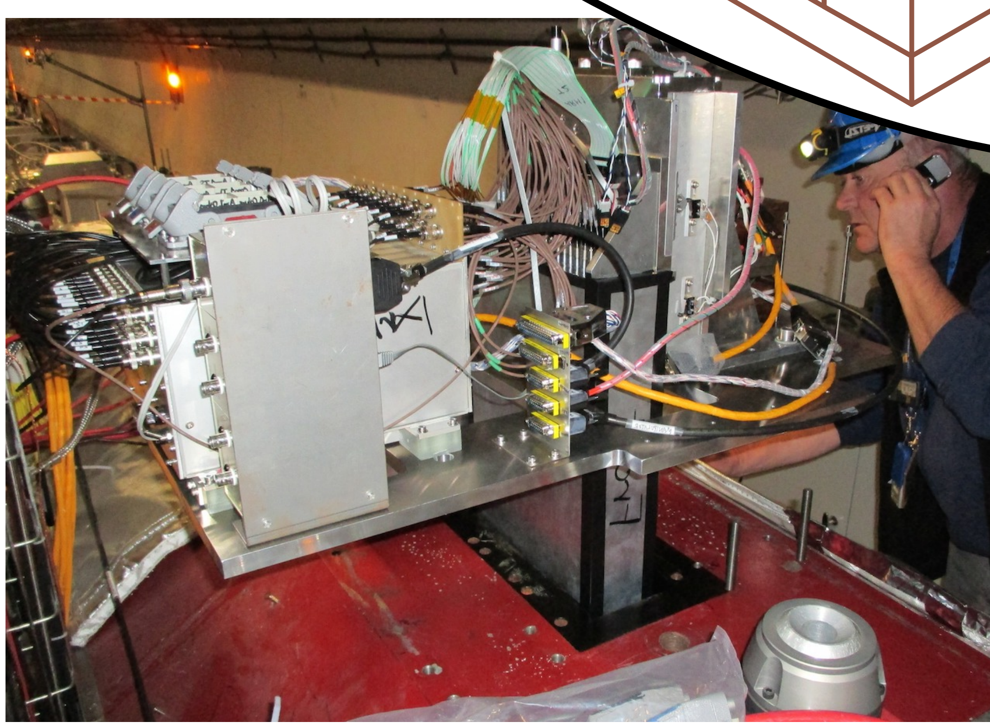
RHICf experiment

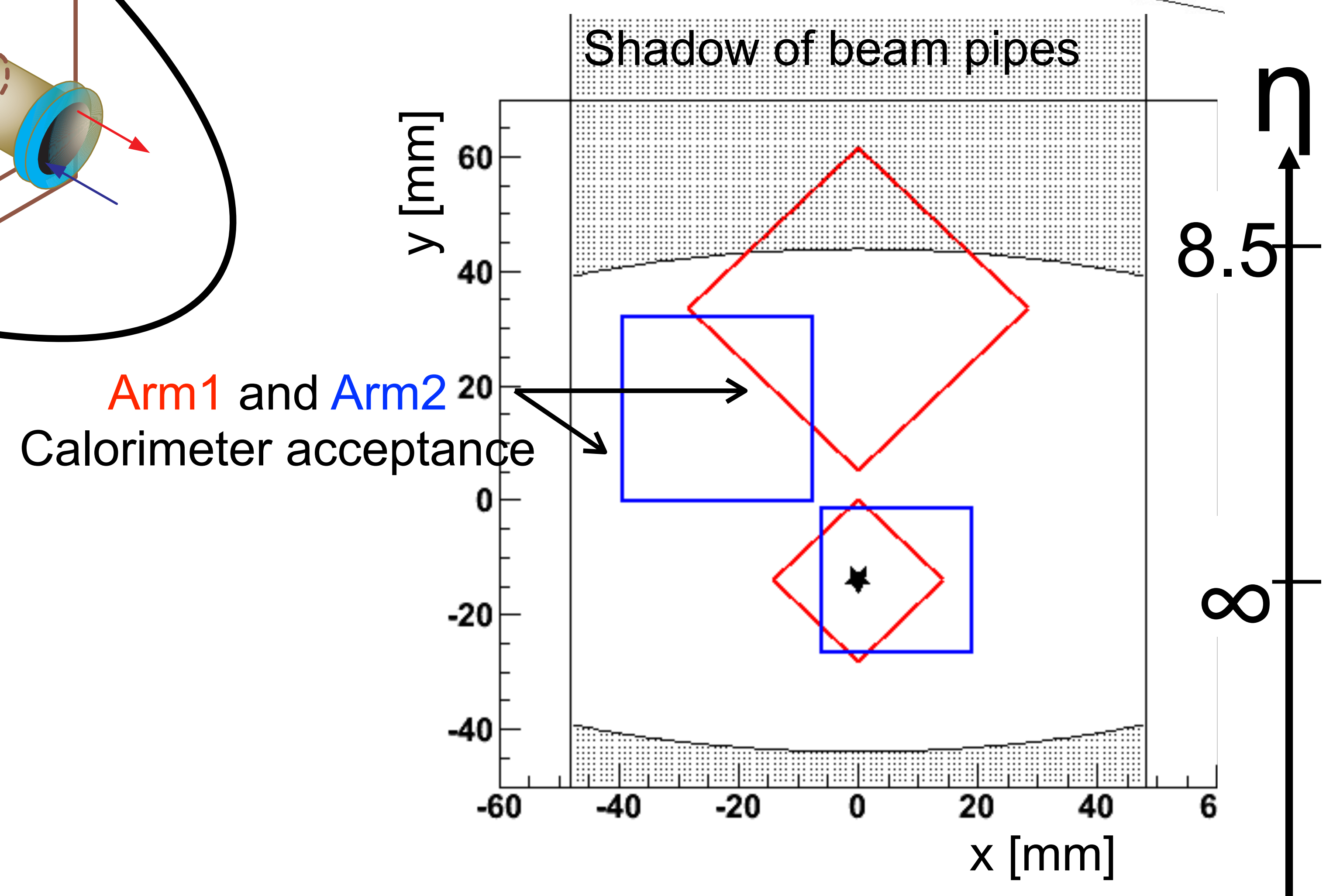
- Zero degree measurement at BNL-RHIC
- Only one detector at 18 m from STAR IP
- Spin asymmetry measurements with polarized proton beams
- Operation: pp $\sqrt{s}$ = 510 GeV (2017)



LHCf experimental setup



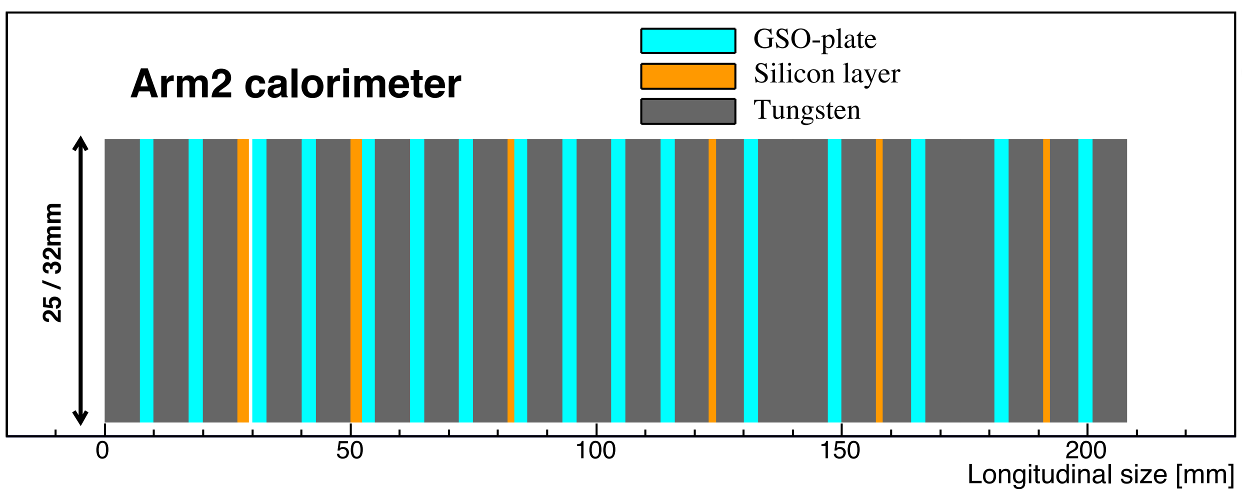


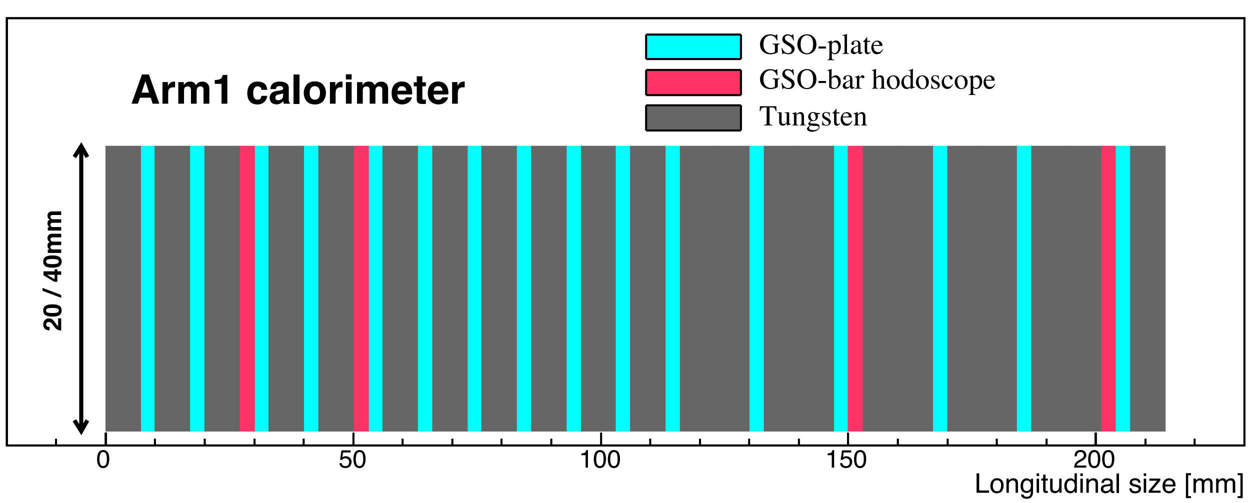


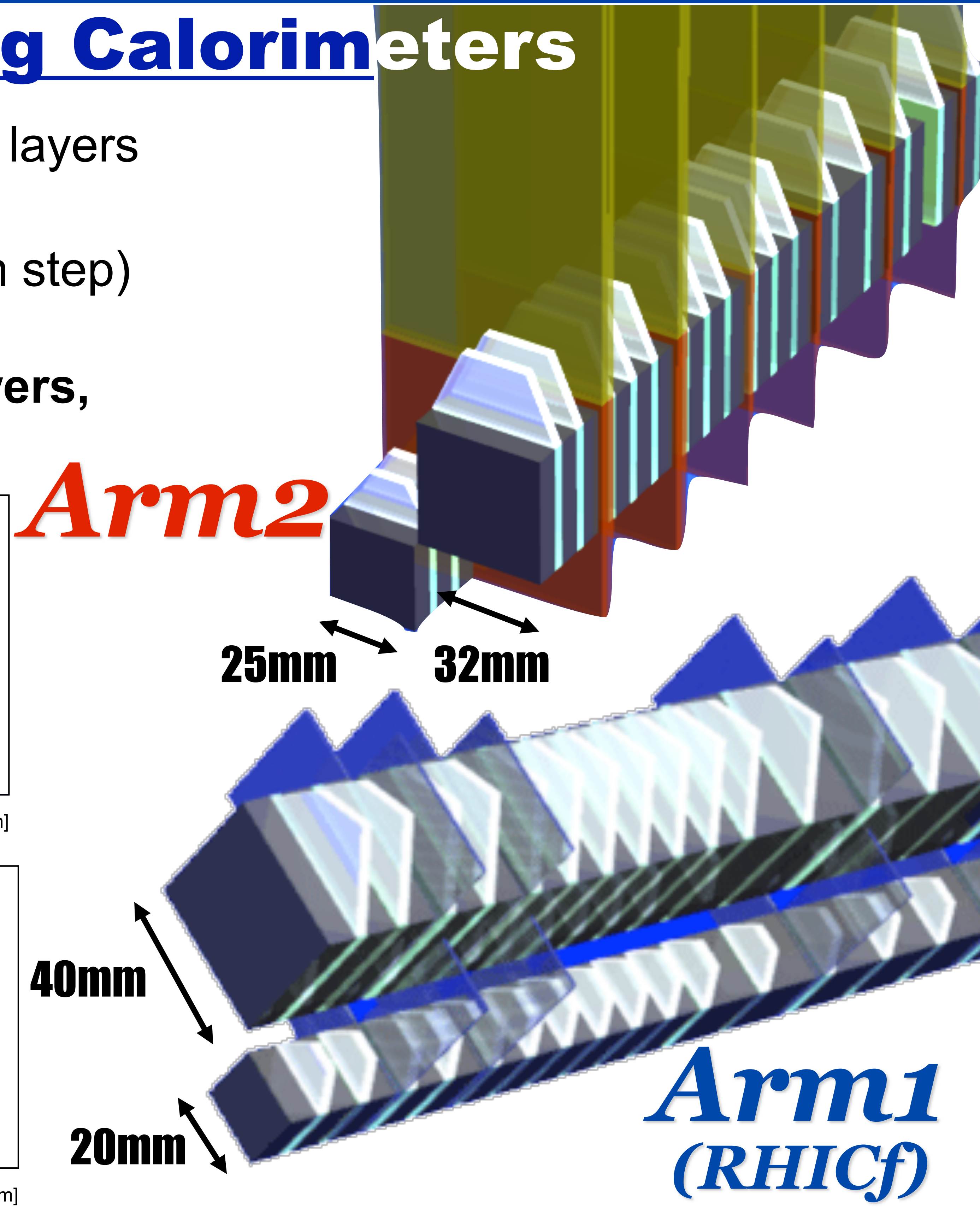
The LHCf/RHICf detectors

Sampling and Positioning Calorimeters

- W (44 r.l , 1.7λ_I) and 16 GSO scintillator layers
- Four positioning sensitive layers;
  Arm1: XY-hodoscope of GSO bars (1mm step)
  Arm2: XY-Silicon strip (160 μm step)
- **Each detector has two calorimeter towers, which allow to reconstruct π^0**

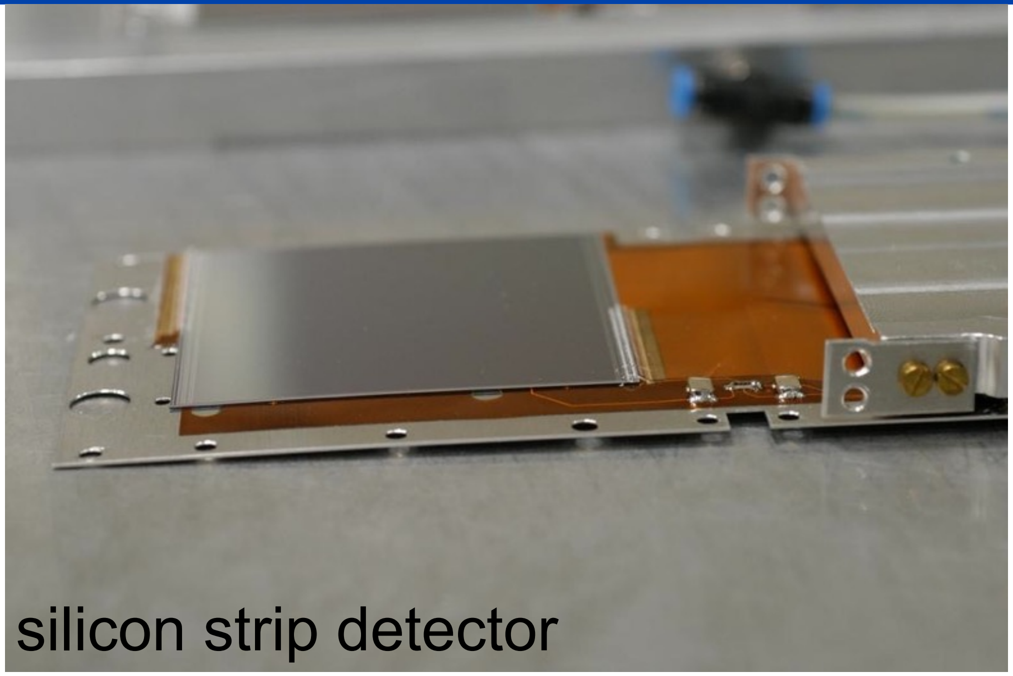


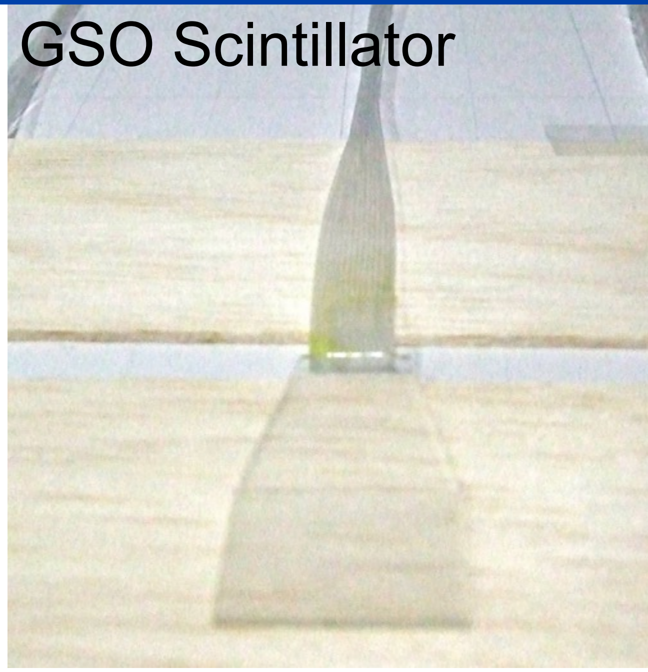


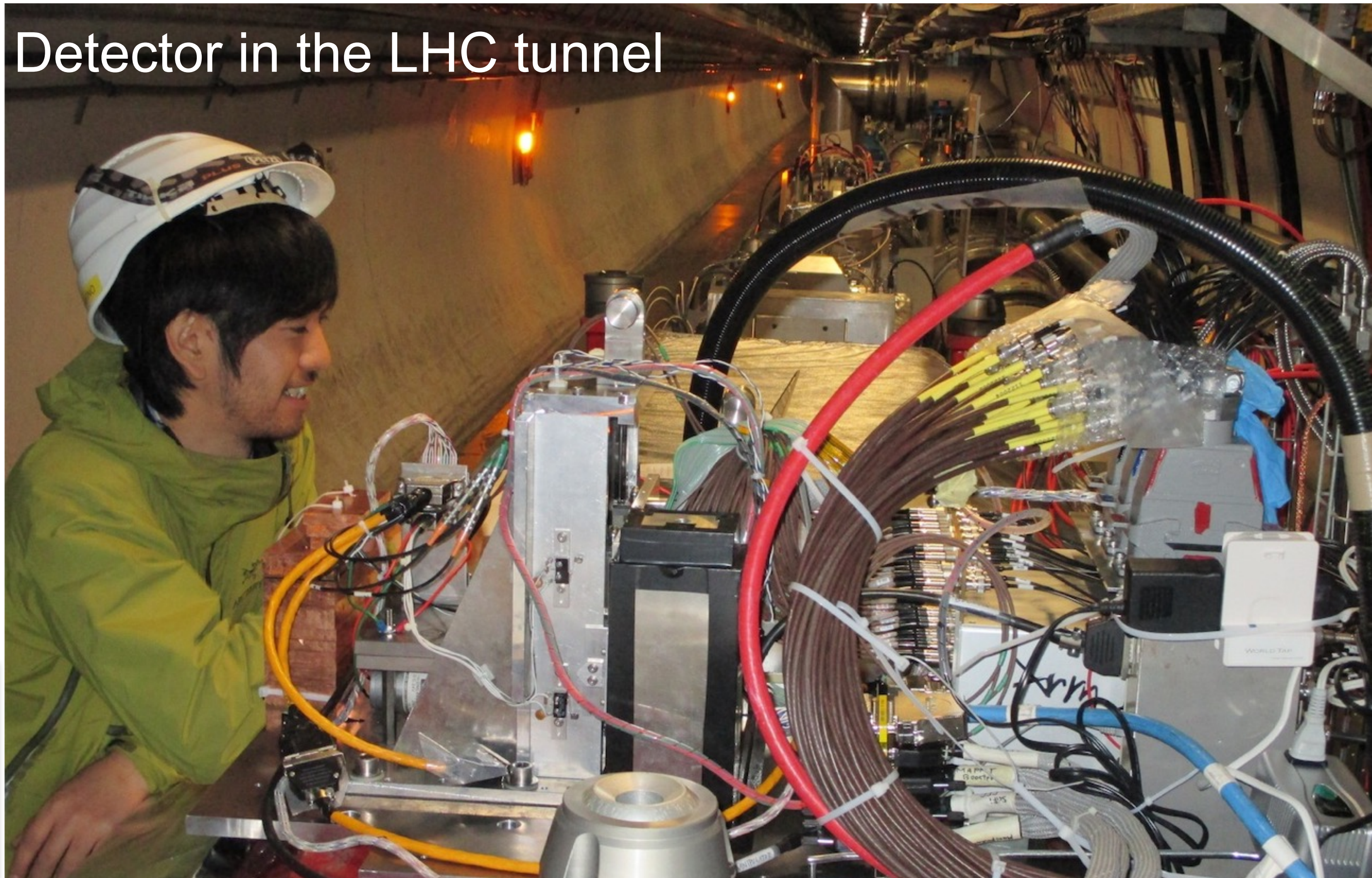


The LHCf detectors


Arm1 Detector


silicon strip detector

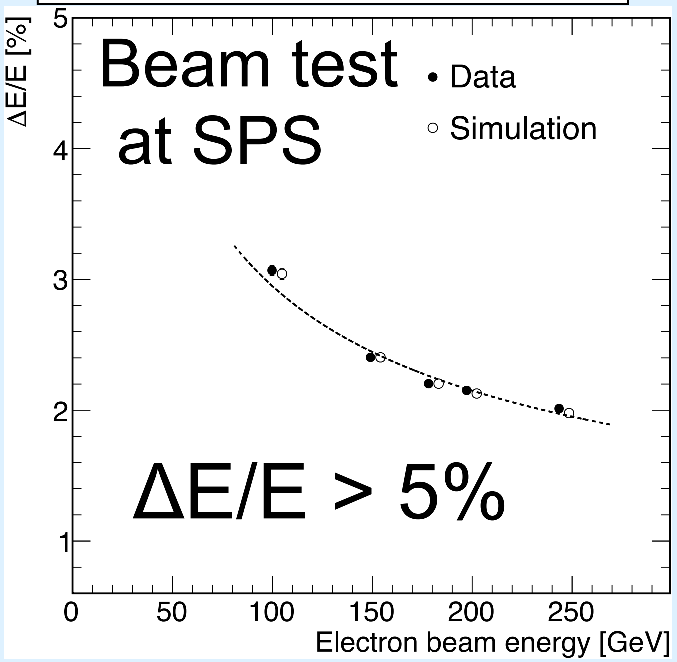

GSO Scintillator


Detector in the LHC tunnel

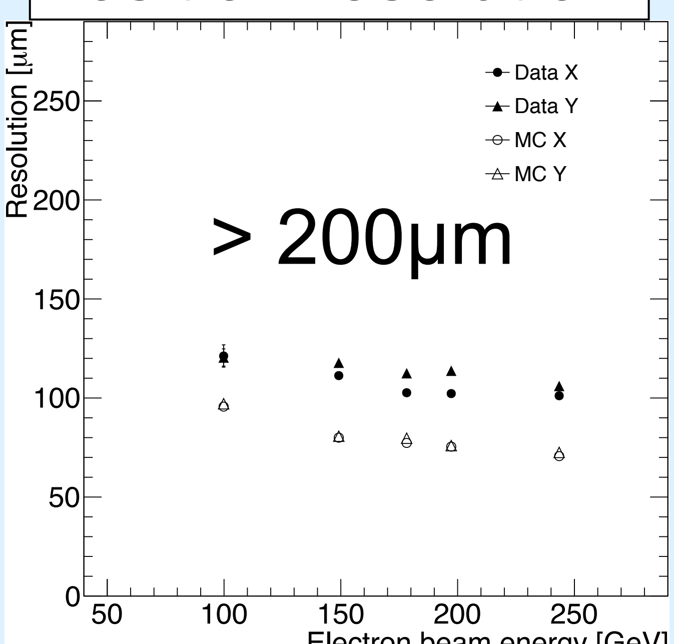
Calorimeter performances

EM showers

Energy resolution

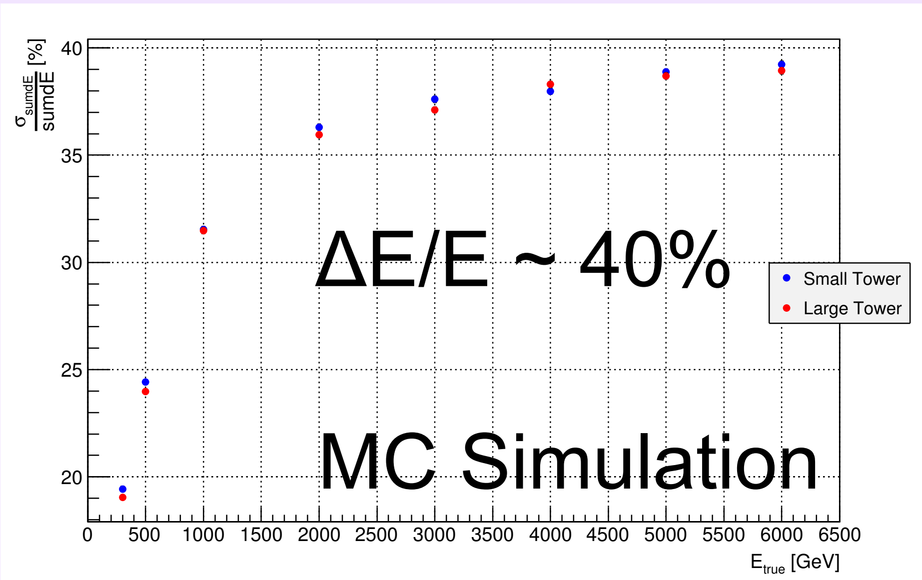


Position resolution

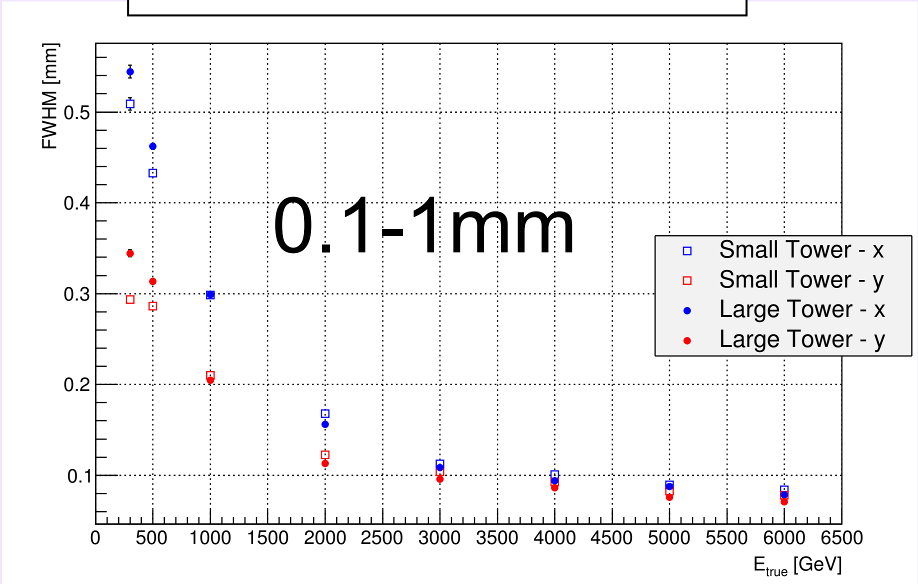


Had. showers

Energy resolution



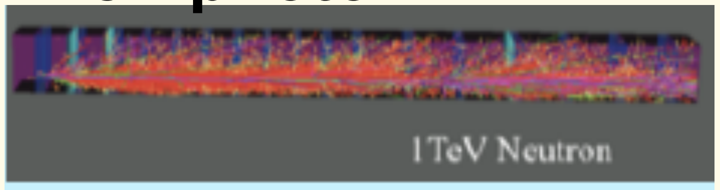
Position resolution



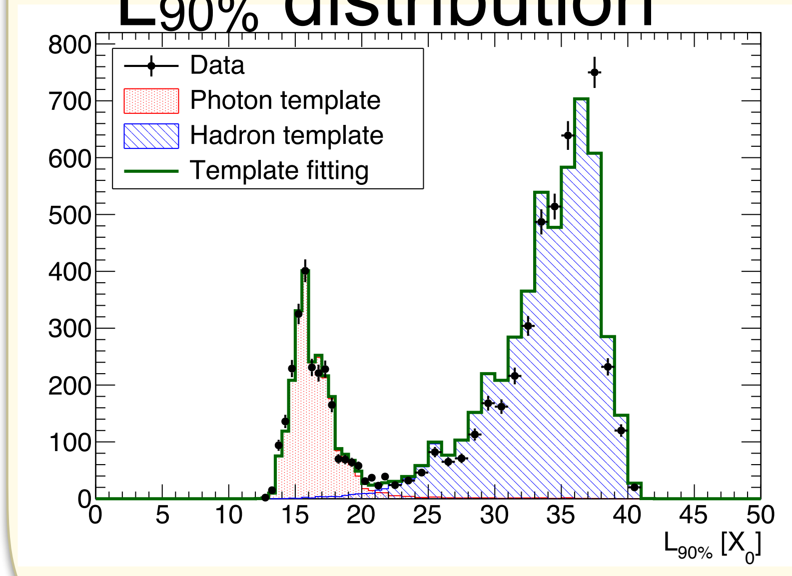
PID

400 GeV photon

1TeV photon



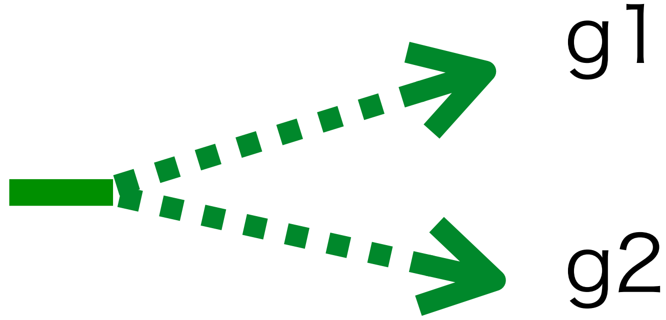
$L_{90\%}$ distribution



LHCf operations and results

Run	E_{lab} (eV)	Photon	Neutron	π^0	
p-p $\sqrt{s}$=0.9TeV (2009/2010)	4.3×10^{14}	PLB 715, 298 (2012)		-	
p-p $\sqrt{s}$=2.76TeV (2013)	4.1×10^{15}			PRC 86, 065209 (2014)	PRD 94 032007 (2016)
p-p $\sqrt{s}$=7TeV (2010)	2.6×10^{16}	PLB 703, 128 (2011)	PLB 750 360 (2015)	PRD 86, 092001 (2012)	
p-p $\sqrt{s}$=13TeV (2015)	9.0×10^{16}	PLB 780, 233 (2018)	JHEP, 2018, 73 (2018)	on-going	
p-Pb $\sqrt{s_{NN}}$=5TeV (2013,2016)	1.4×10^{16}			PRC 86, 065209 (2014)	
p-Pb $\sqrt{s_{NN}}$=8TeV (2016)	3.6×10^{16}	Preliminary			
RHICf p-p $\sqrt{s}$=510GeV (2017)	1.4×10^{14}	on-going			

π^0 measurement



$\pi^0 \rightarrow 2\gamma$

$c\tau$ = 25nm

BR = 99.8%

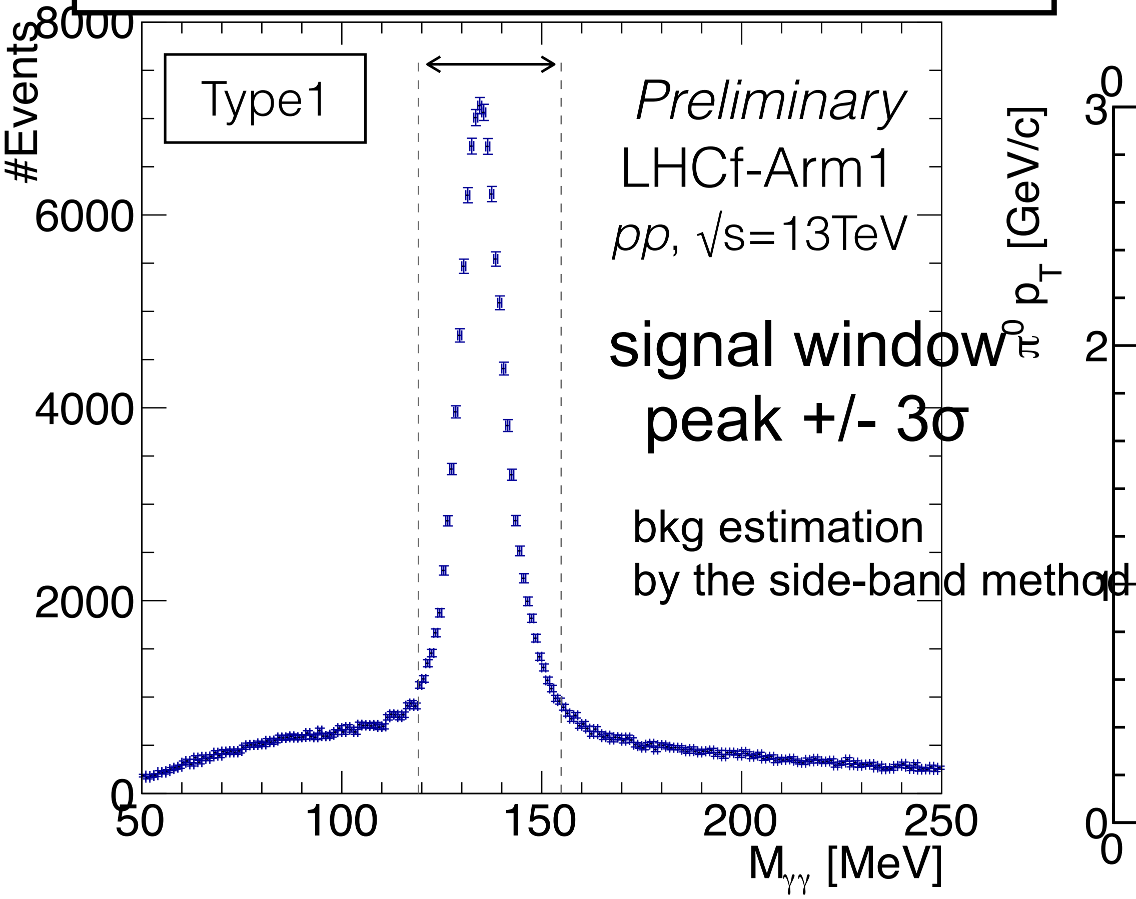
$$\begin{cases} E_{\pi 0} = E_{g1} + E_{g2} \\ M_{\pi 0} = \sqrt{E_{g1} E_{g2} \theta^2} \end{cases}$$

θ :oping angle btw g1 and g2

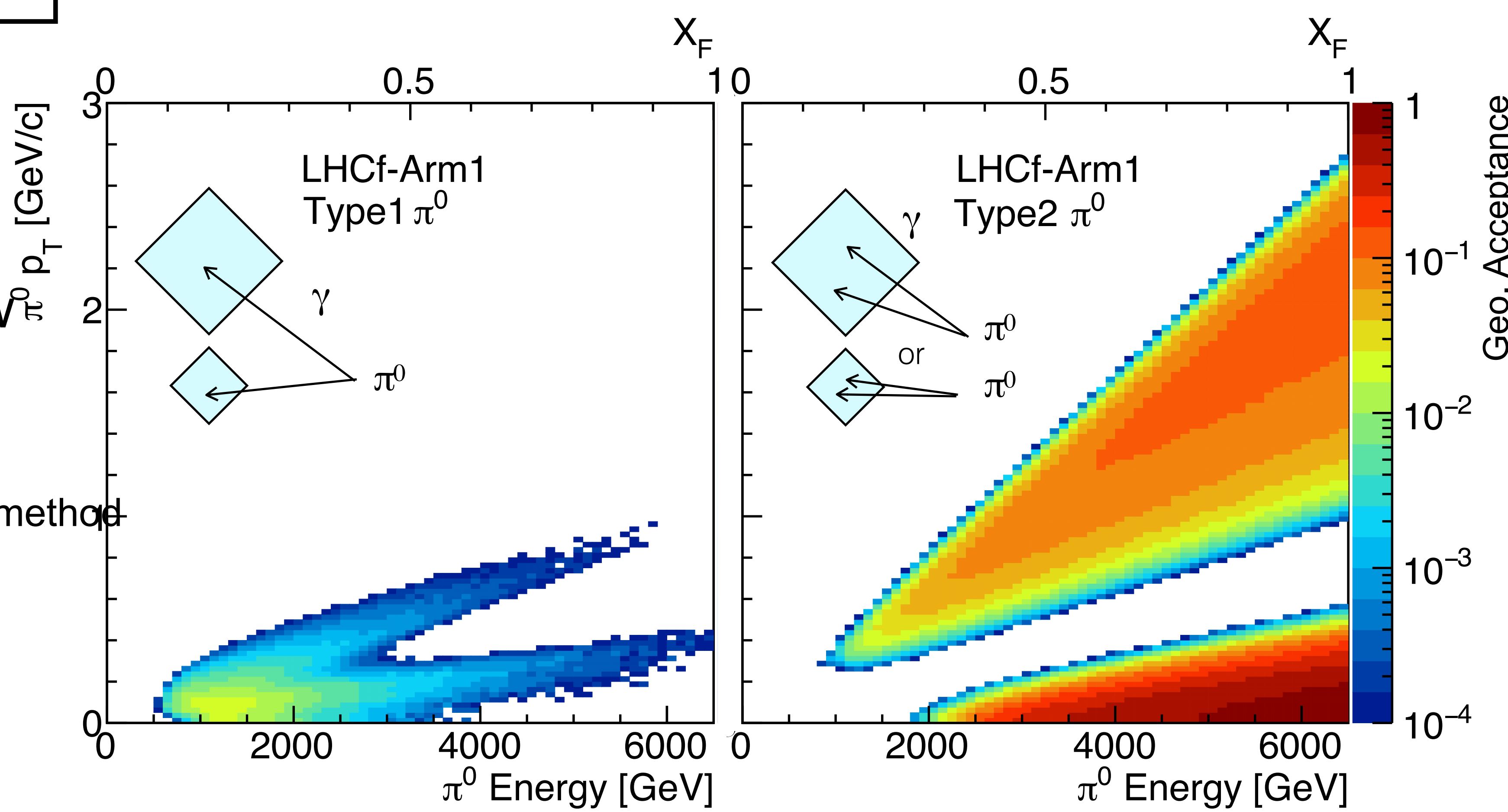
Data

- 3 + 5 hour operations in June 2015
- Arm1, one detector position
- Dedicated trigger for Type1 events

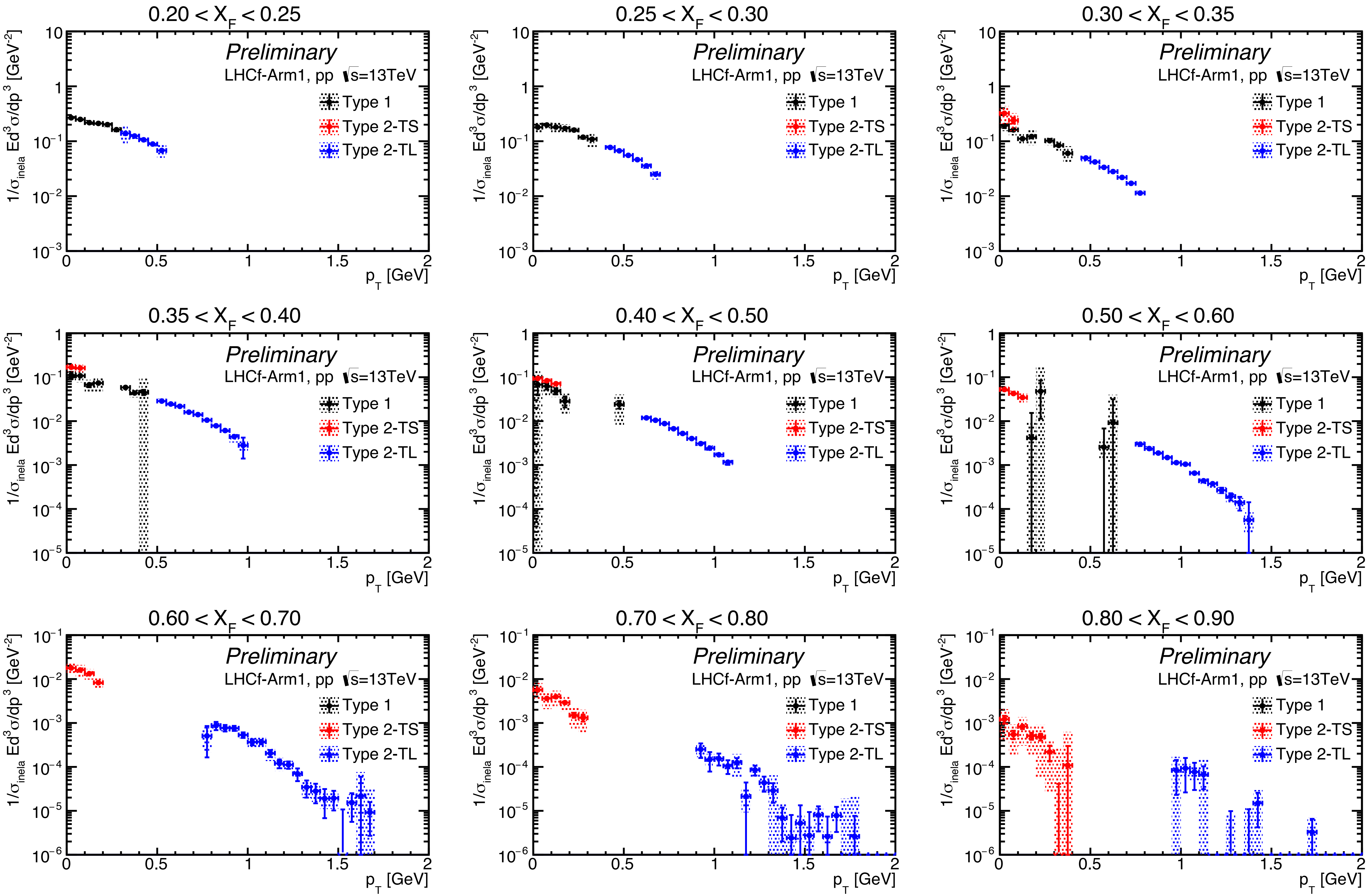
reconstructed mass distribution



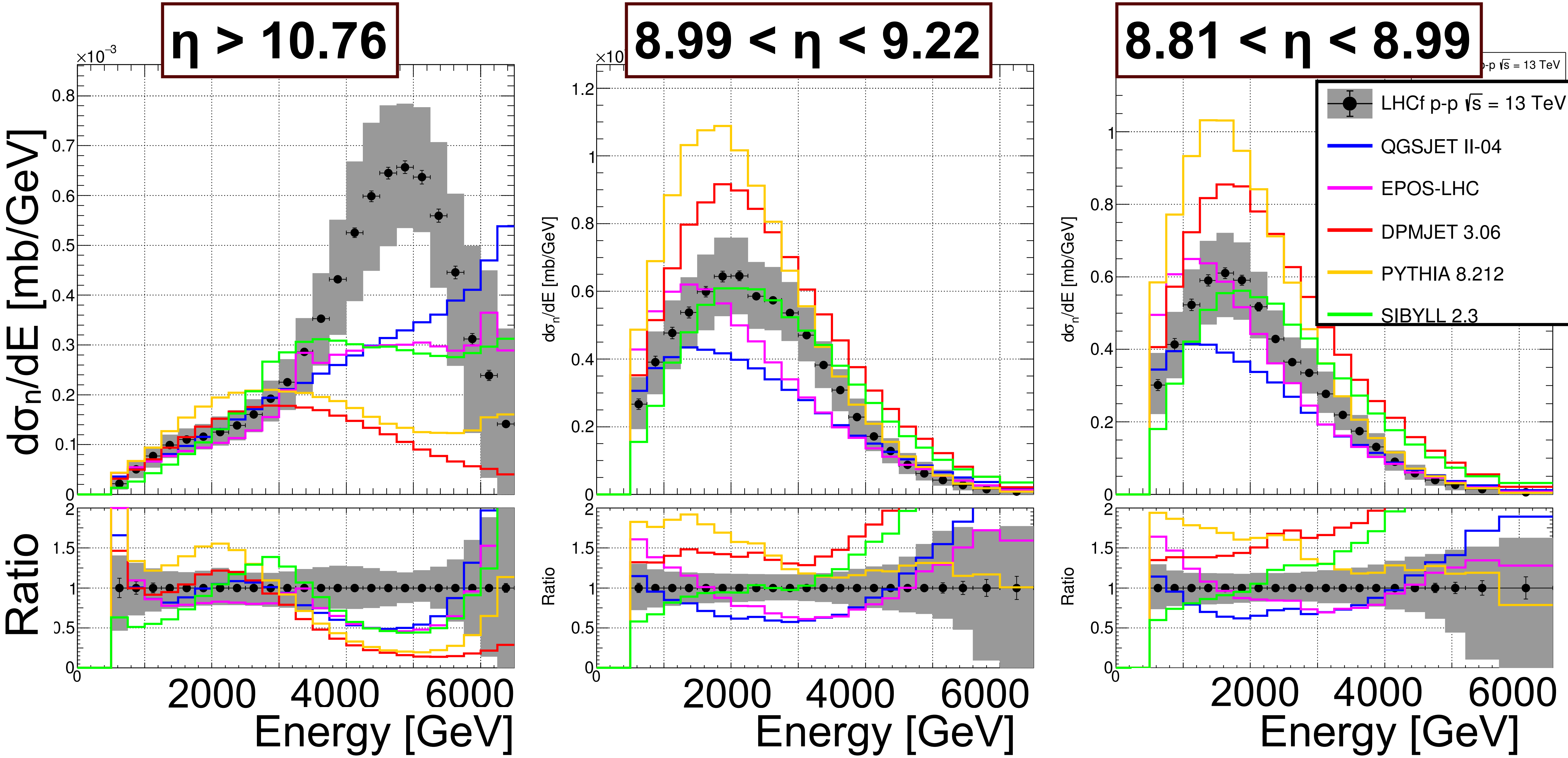
Geometrical Acceptance



π^0 spectra at *pp*, $\sqrt{s}$ = 13 TeV

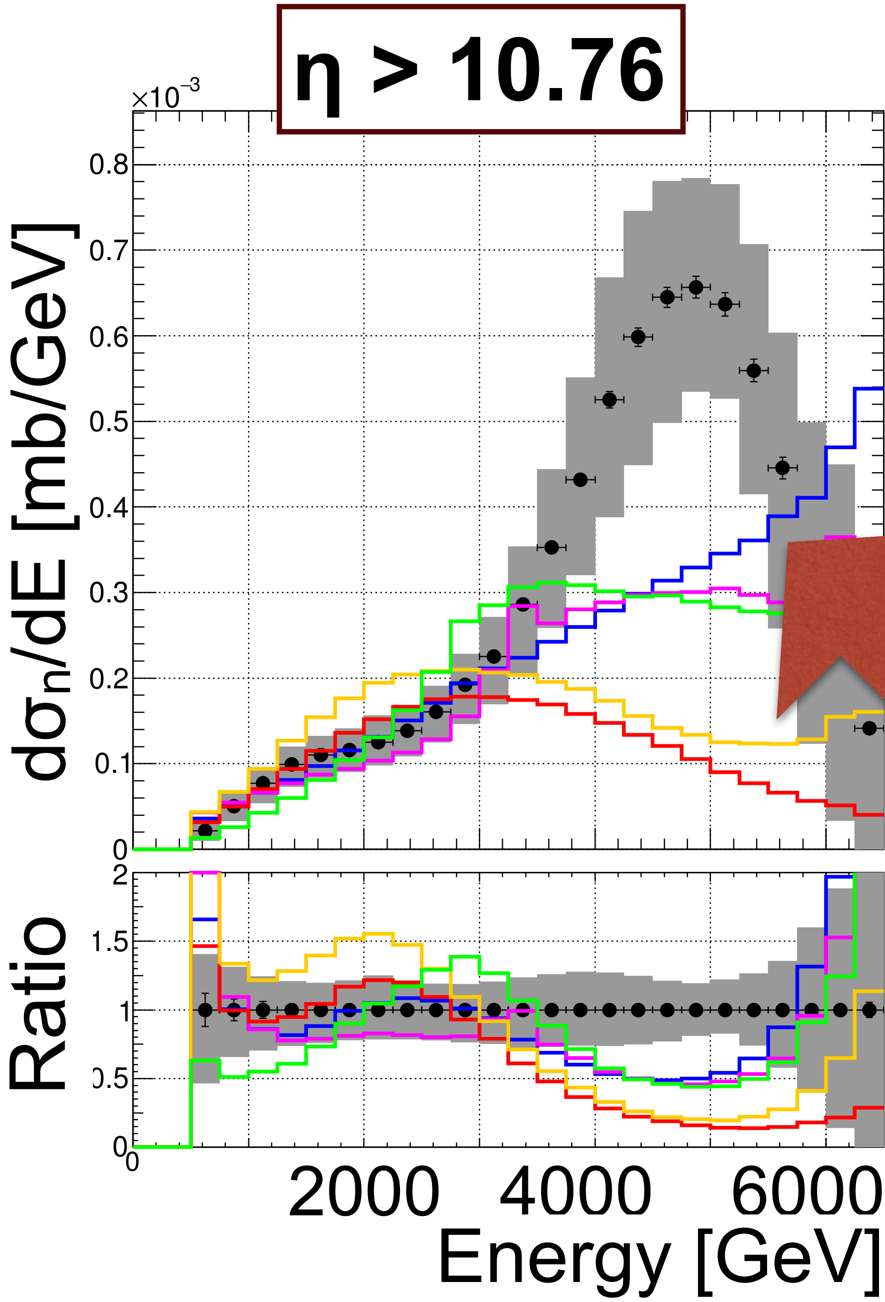


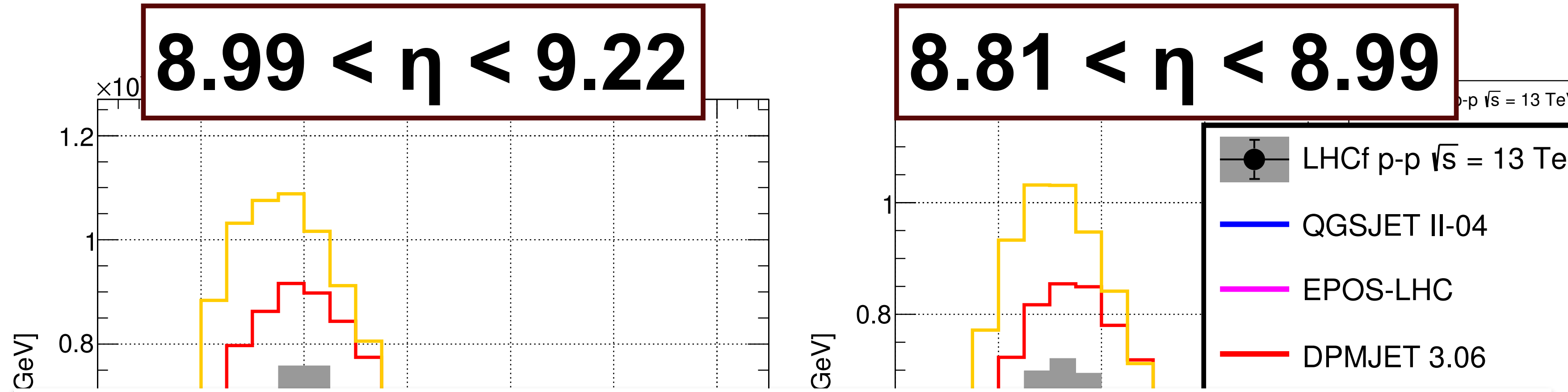
Neutron spectra, *pp* √s=13TeV

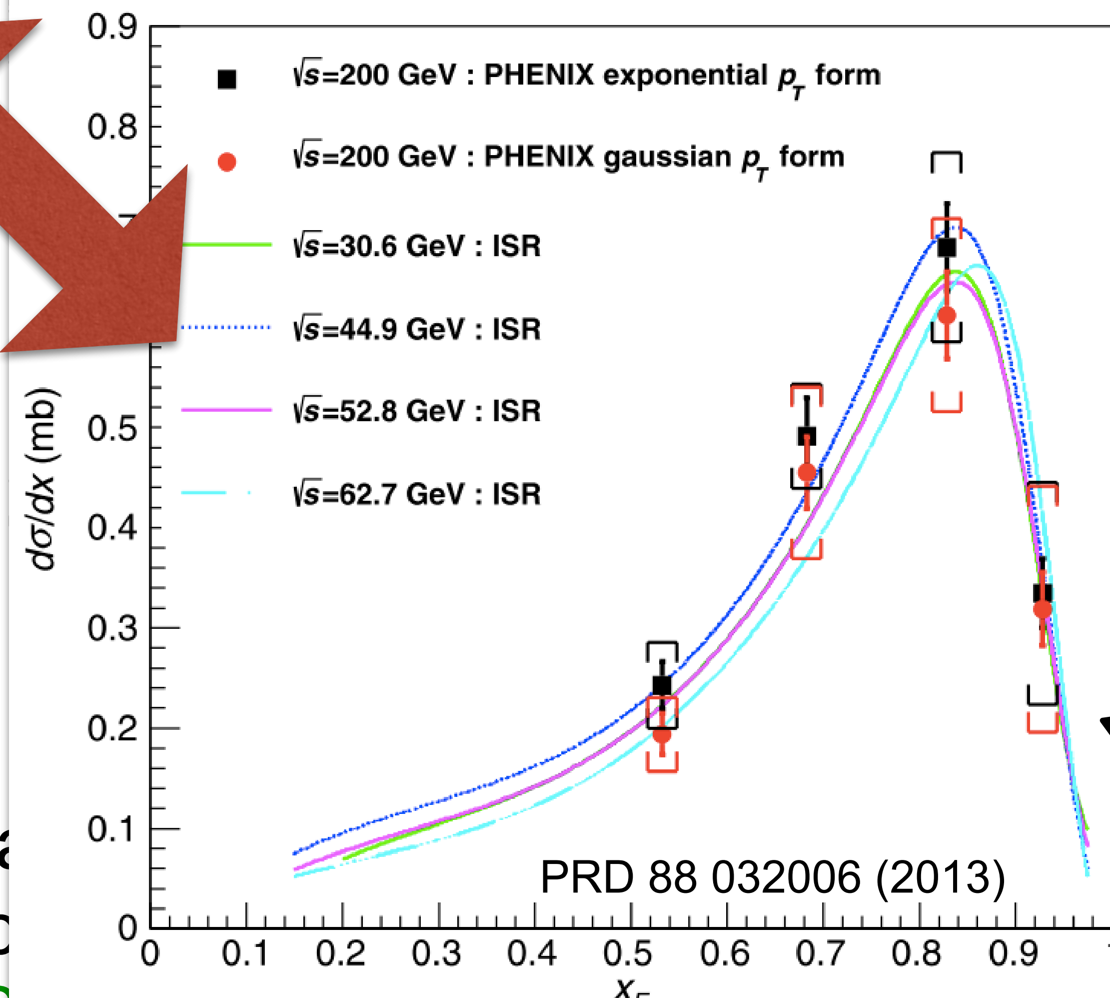


- In η > 10.76, data shows a strong increasing of neutron production in the high energy region. This behavior is not predicted by all models.
- EPOS-LHC and SIBYLL 2.3 have the best agreement in 8.99 < η < 9.22, 8.81 < η < 8.99, respectively.

Neutron spectra, *pp* √s=13TeV







Forward neutrons @ RHIC, ISR

The peaked spectra are explained by a one-pion exchange model.

Detailed comparison is needed

$p_T < 0.11\ X_F$

⇕

$p_T < 0.28\ X_F$ @ η>10.76, 13TeV

- In η > 10.76, data shows a high energy region. This b
- EPOS-LHC and SIBYLL 2 8.81 < η < 8.99, respectively.

Joint analysis with ATLAS

ATLAS-CONF-2017-075

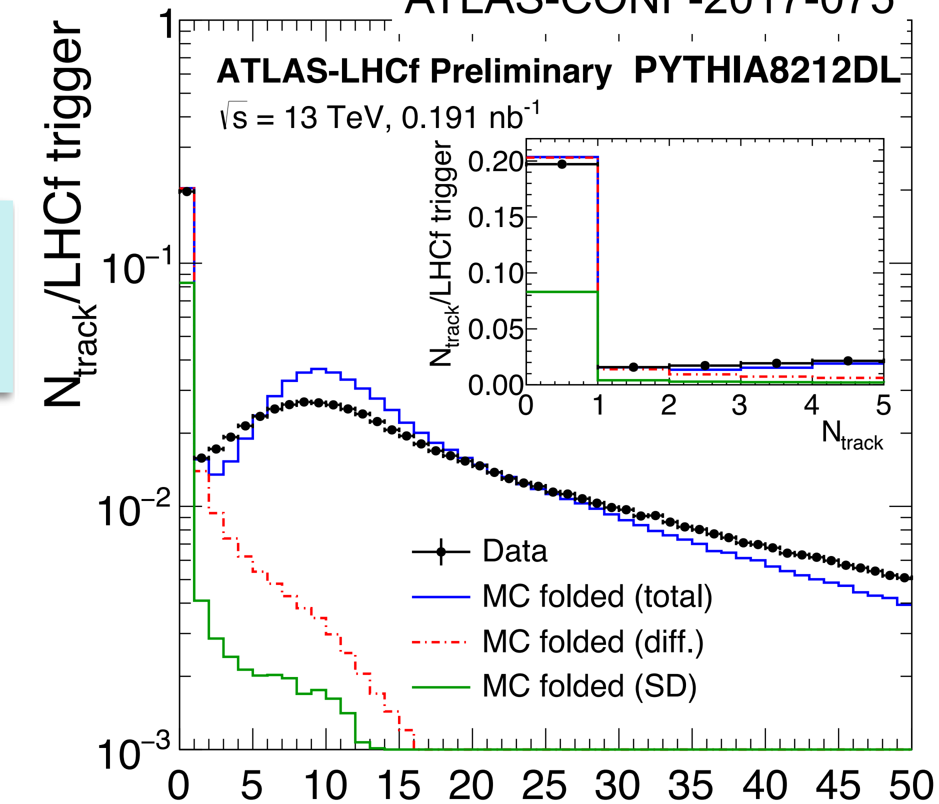
Identification of diffractive events by ATLAS

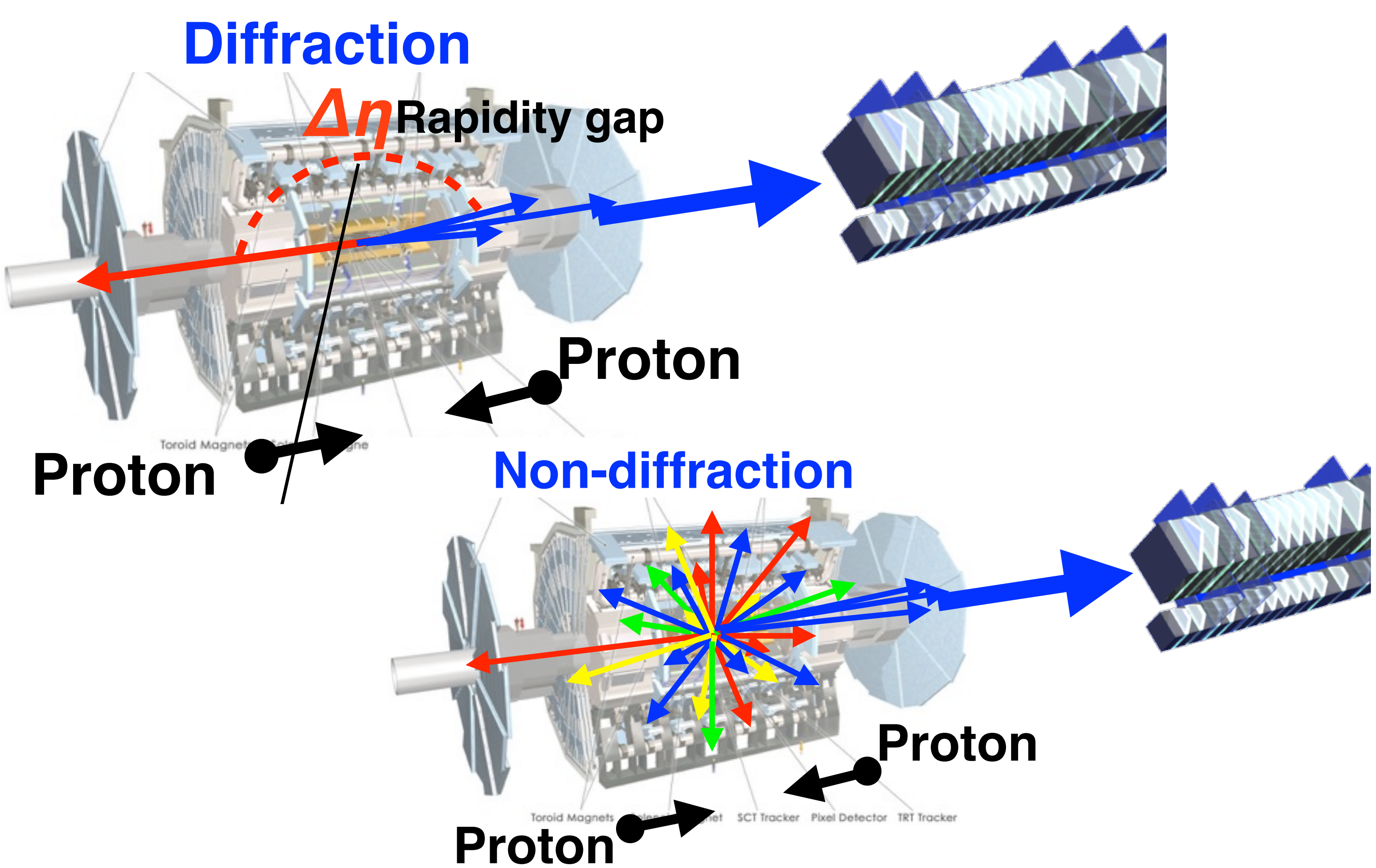
Method

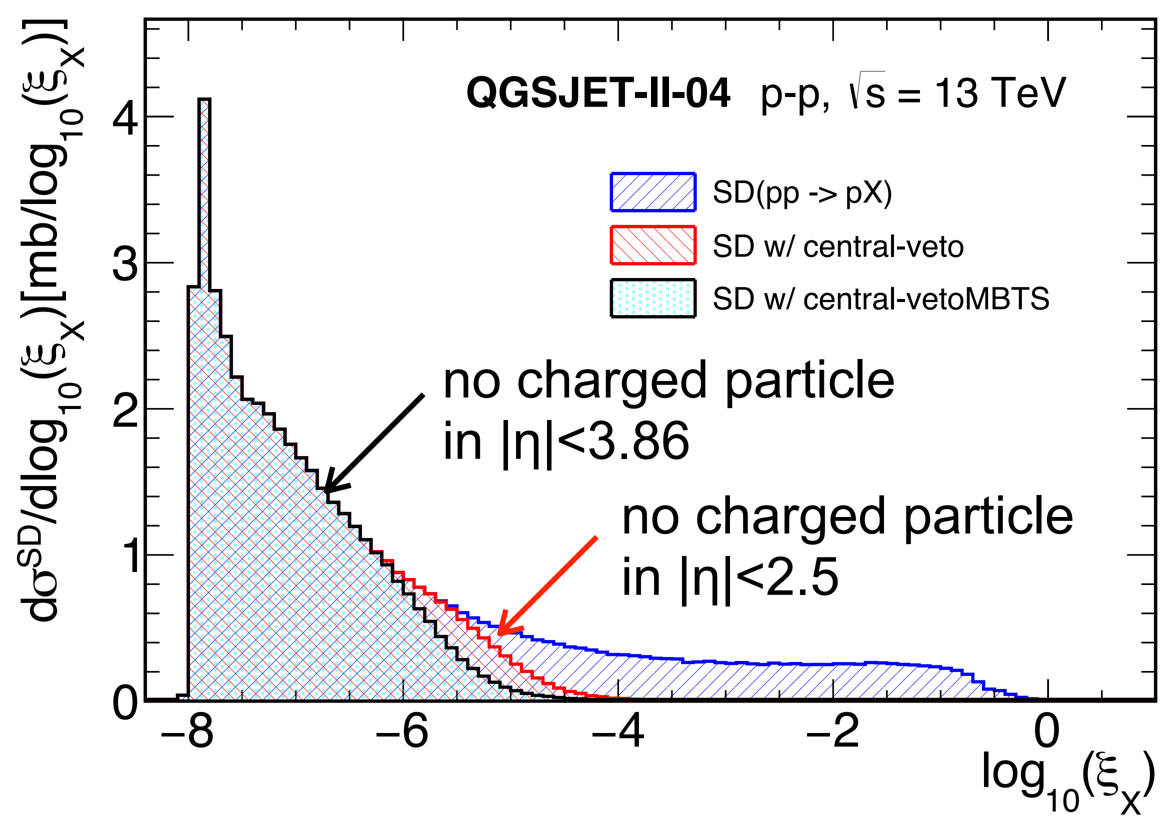
- Event selection by N_{tracks}=0 ⇔ Large rapidity gap $\Delta\eta > 5$

N_{tracks}: the number of tracks detected **by ATLAS inner trackers** ($|\eta|<2.5$, $p_T > 100$ MeV)

→ Selecting pure samples of proton dissociations.
→ Sensitive to only low-mass dissociations $M_X \lesssim 50$ GeV





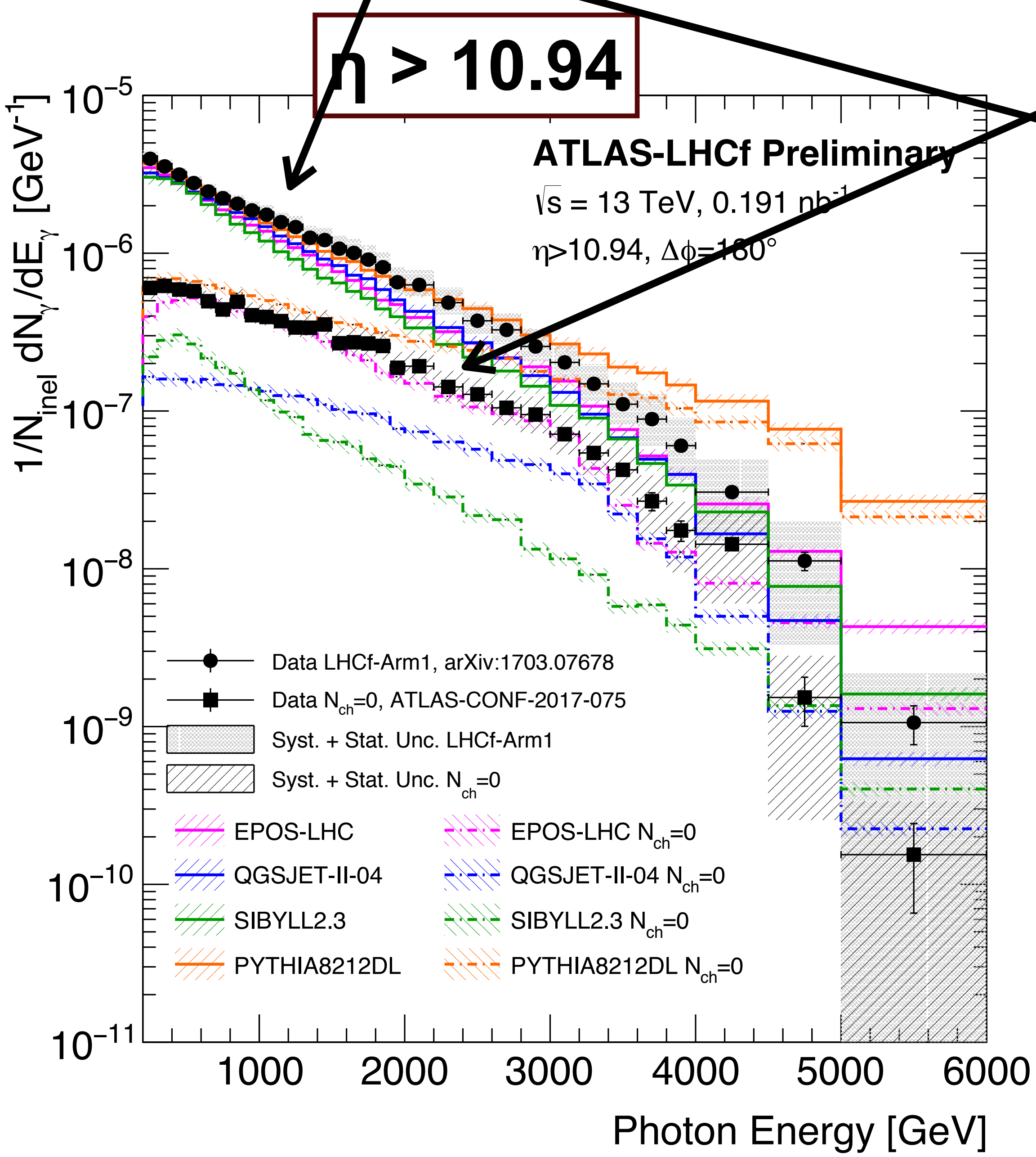


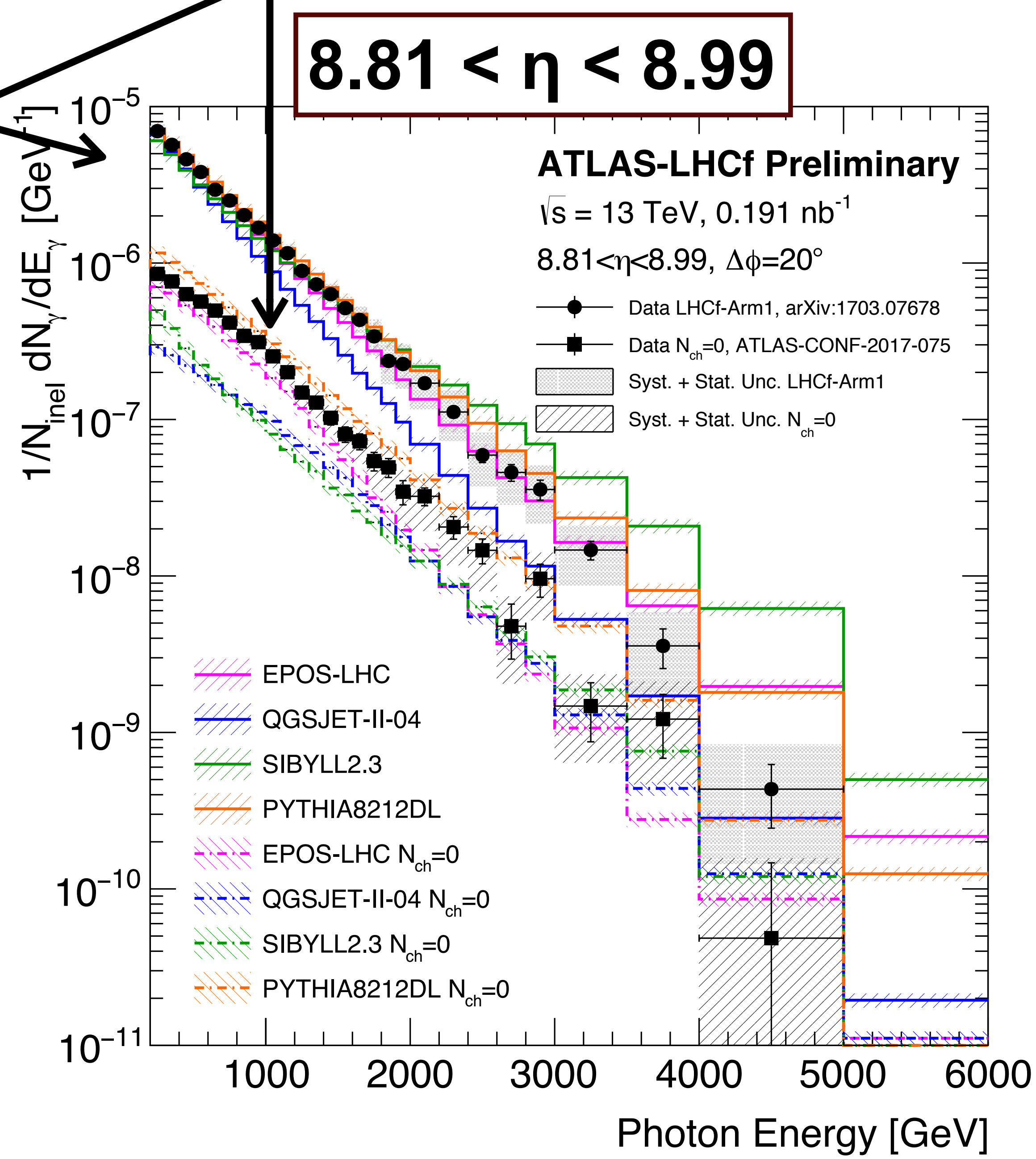
Measurement of contributions of diffractive processes to forward photon spectra in *pp* collisions at √s = 13 TeV

Preliminary result of the measurement for forward photons is published in a conference-note; ATLAS-CONF-2017-075

Inclusive photon spectra

Photon spectra w/ N_{ch} = 0 selection





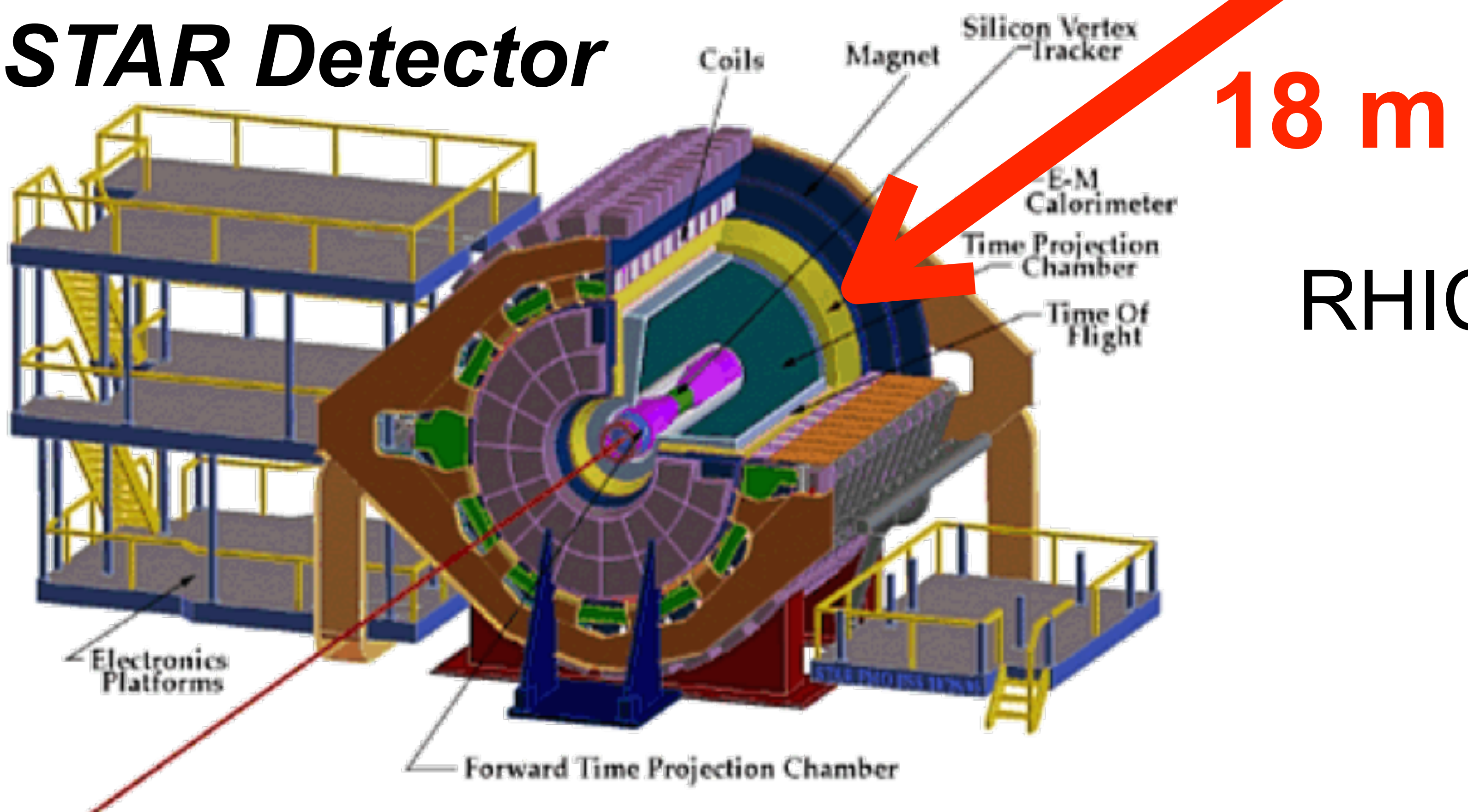
RHICf experiment

RHICf experiment

RHIC at BNL

- ***pp*** **$\sqrt{s}$ = 510 GeV**
  (polarized beam)
- Test of energy scaling with the wide p_T range.
- The operation was successfully completed in June 2017
- Common operation with STAR

STAR Detector



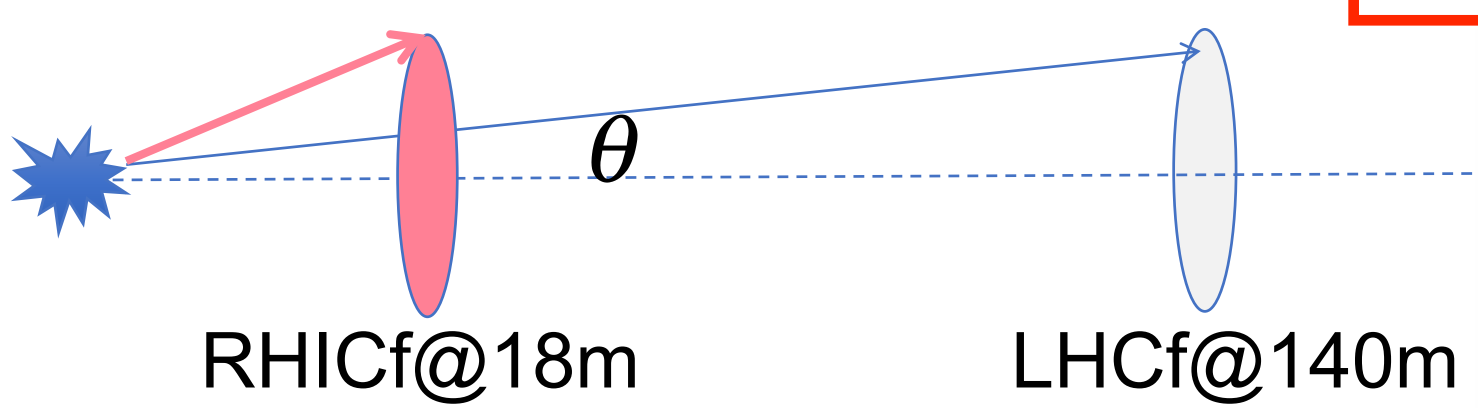
RHICf coverage:
$\eta > 6$

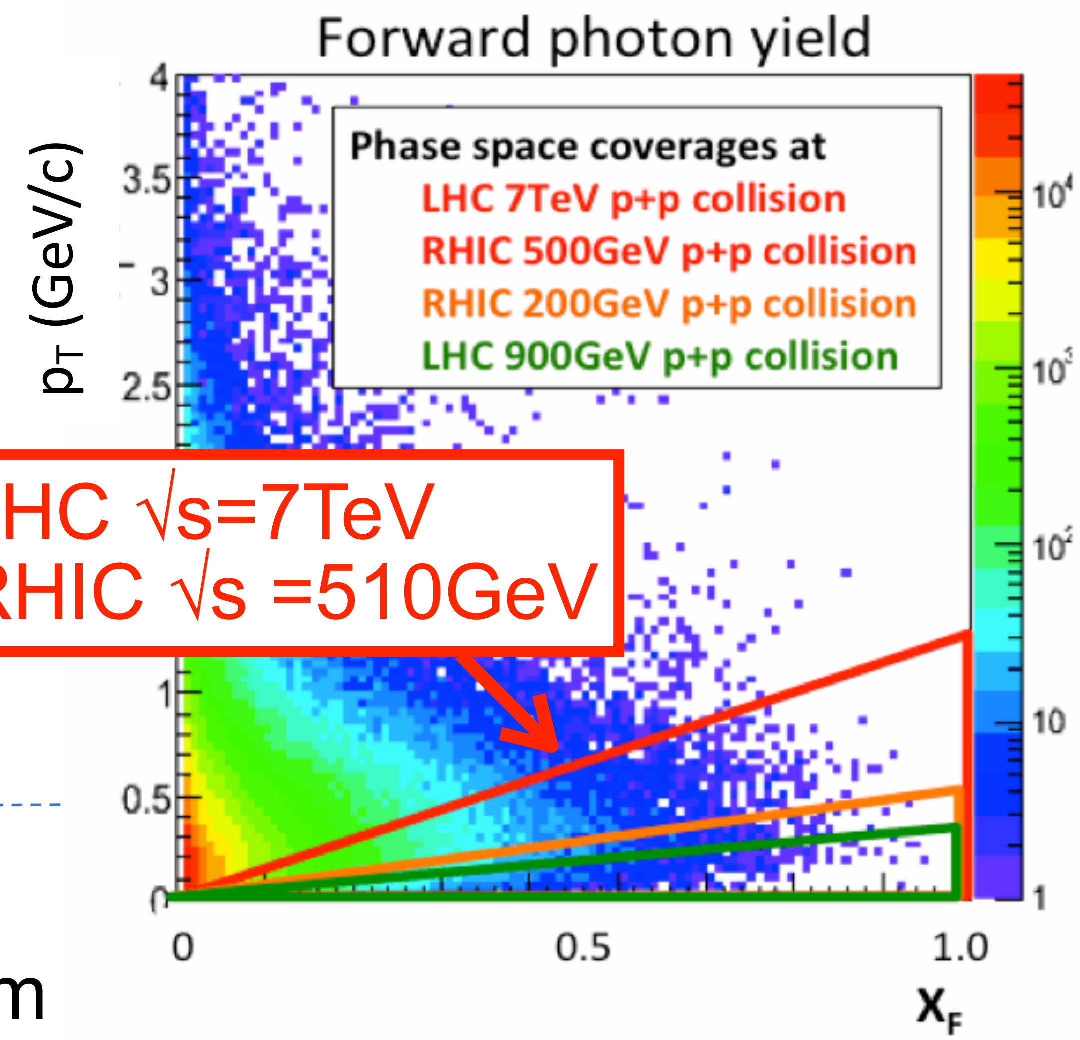
Physics in RHICf

Cross-section measurement

✓Measurement of √s dependency (=Energy scaling) with the wide p_T range equivalent to LHCf,√s=7TeV
→ Improve the prediction power of models in the wide energy rage.

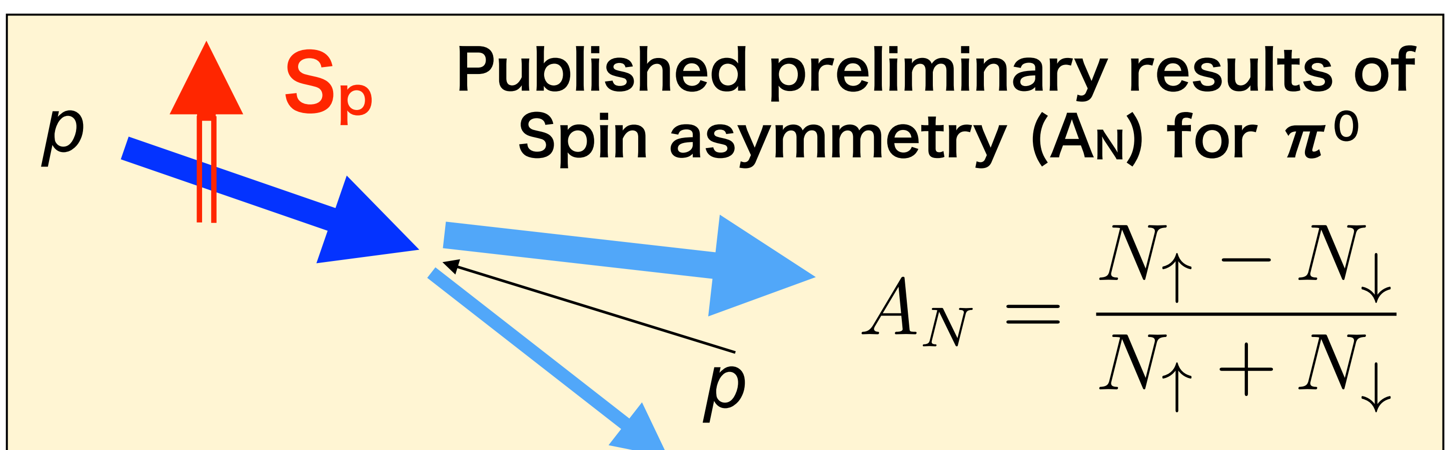
p_T coverage: < 1/2 √s sinθ





Spin asymmetry measurement

A PhD student, M. Kim, is completing π^0 asymmetry measurement (next pages)

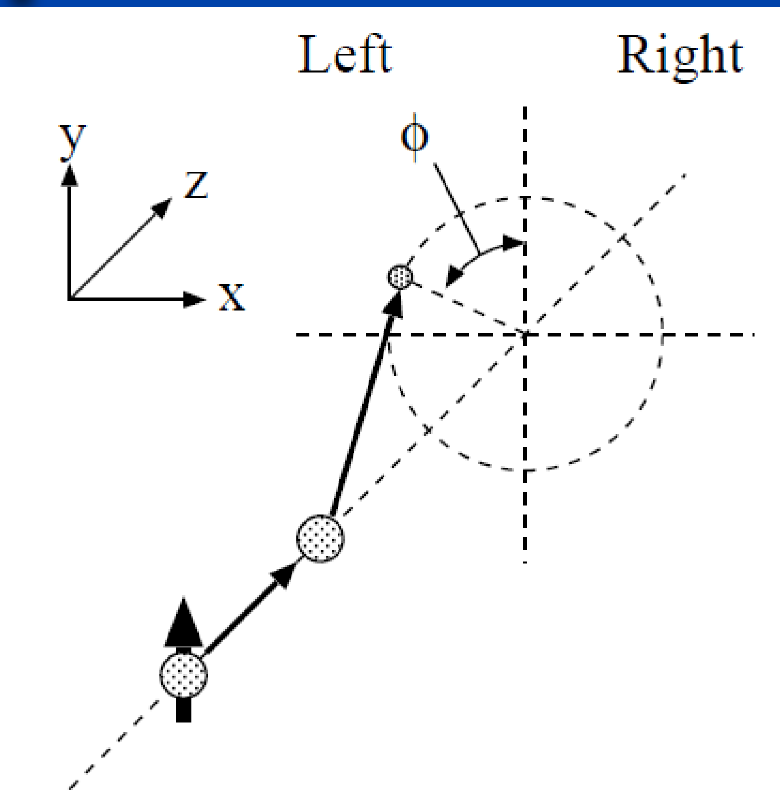


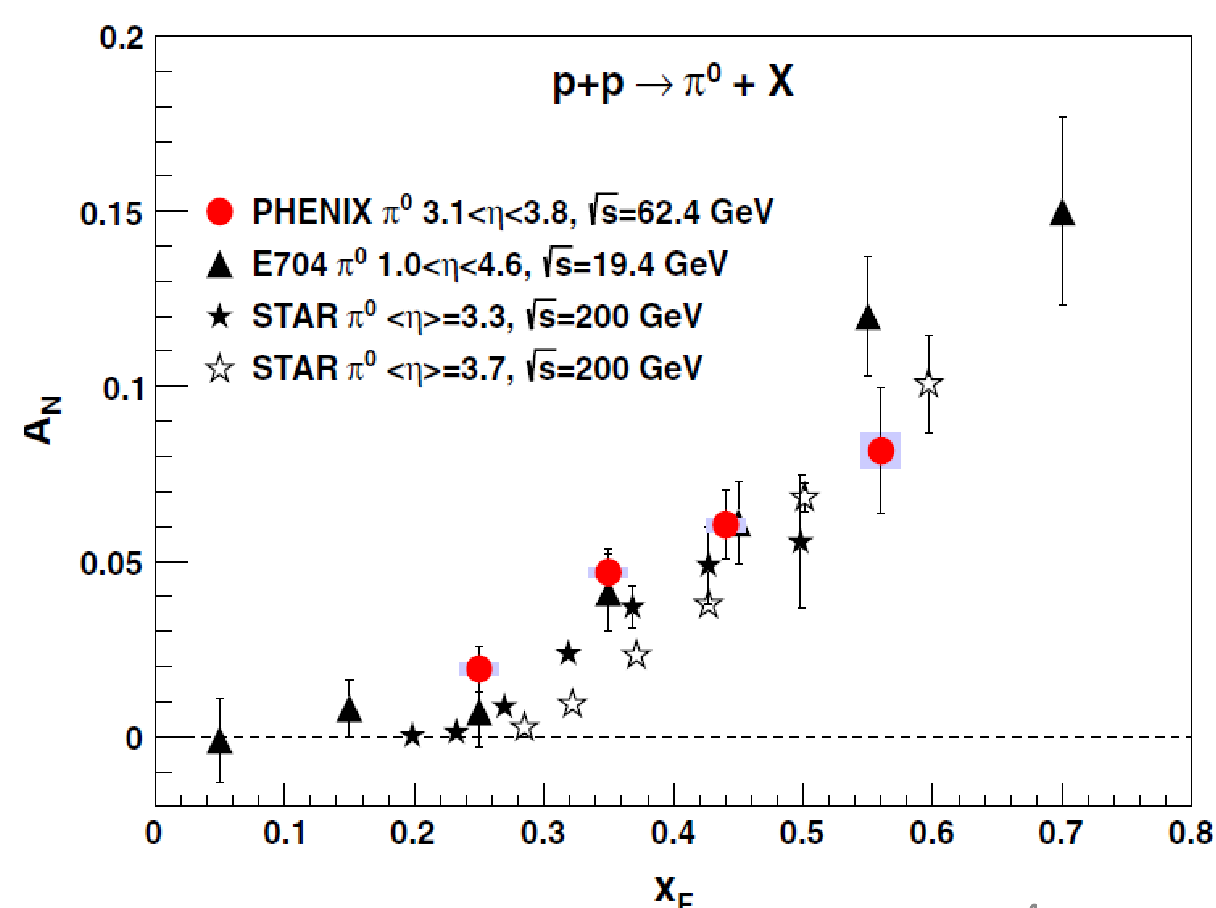
spin asymmetry of π^0 production

- AN (transverse single-spin asymmetry) measurement

$$A_N = \frac{d\sigma_{Left} - d\sigma_{Right}}{d\sigma_{Left} + d\sigma_{Right}}$$

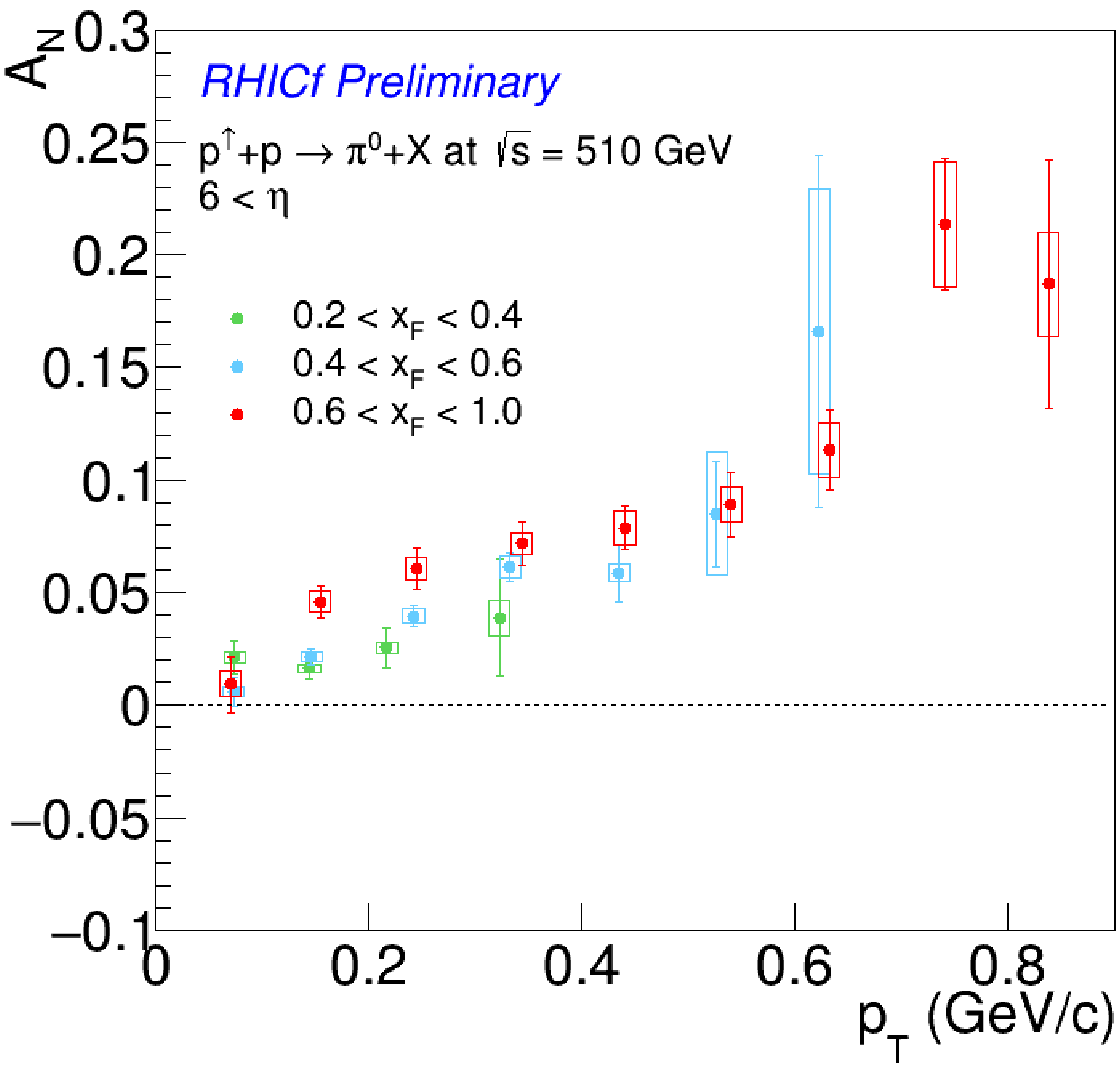
- Large asymmetry was found in $1 < \eta < 4$ (p_T>~1GeV/c)
- Explanations
  - Initial-stat effect ? final-stat effect ?
- Questions
  - A_N in the very forward region ? The RHICf detector covers $\eta > 6$, $p_T < 1$GeV/c.





RHICf result: π^0 spin asymmetry

- Large asymmetry (up to 0.1 GeV/c) even at low p_T ($p_T <$ 0.6 GeV/c)
- Becoming large (more than 0.1 GeV/c) at high p_T ($p_T >$ 0.6 GeV/c)



Data:

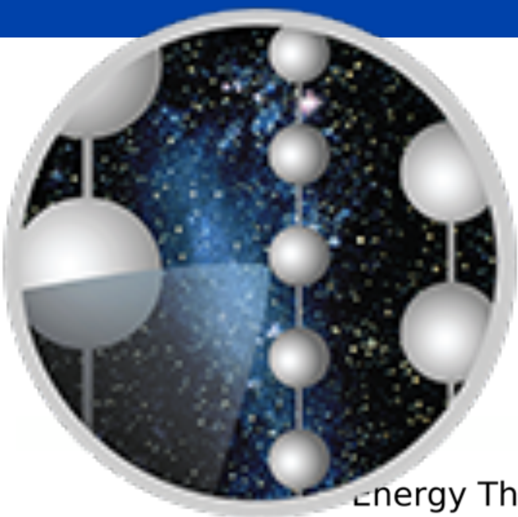
- RHICf 2017 operation with *pp* $\sqrt{s}$ = 510GeV
- Use both type1 and type2 π^0 samples

Error bars : statistics
Error box : systematic

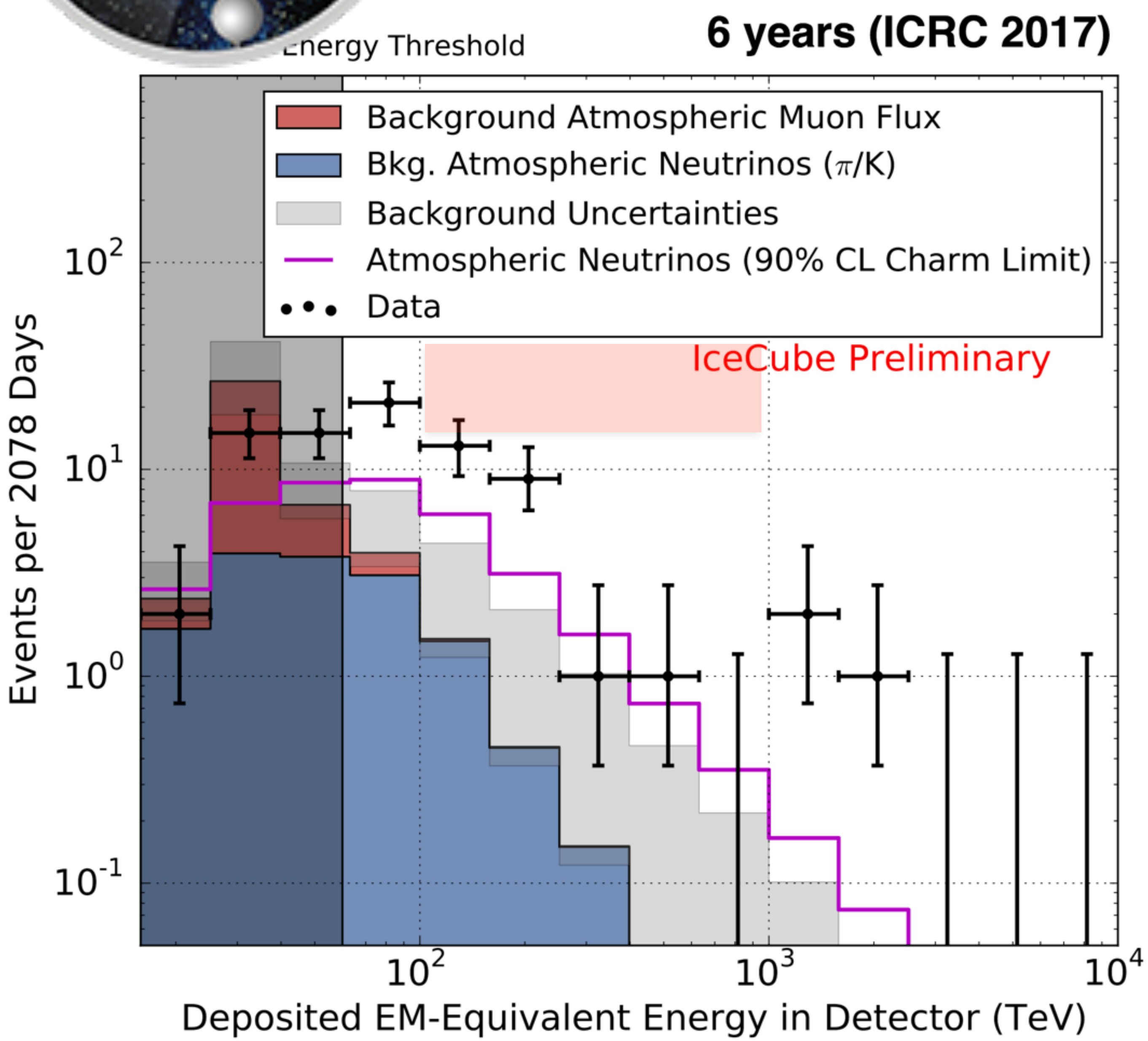
Future plans of LHCf/RHICf

- Operations at LHC, LHC-Run3
  - *pp*, $\sqrt{s}$=13 or 14TeV again
    - Increasing the statistics of π^0 and common events with ATLAS
    - measurement of η ($\eta \rightarrow 2\gamma$), K^0_s ($K^0_s \rightarrow 2\pi^0 \rightarrow 4\gamma$)
    - common-operation with ATLAS RP and ZDC
  - *p*O (OO) collisions
    - Ideal for studying the cosmic-ray interactions of CR-Air
    - Measurement of nuclear effect at light ion collisions
- Operation at RHIC
  - *pp* $\sqrt{s}$=510GeV again in 2022.
    - Increase the statistics of π^0
    - measurement of η ($\eta \rightarrow 2\gamma$), K^0_s ($K^0_s \rightarrow 2\pi^0 \rightarrow 4\gamma$)

Kaons in atm. ν productions

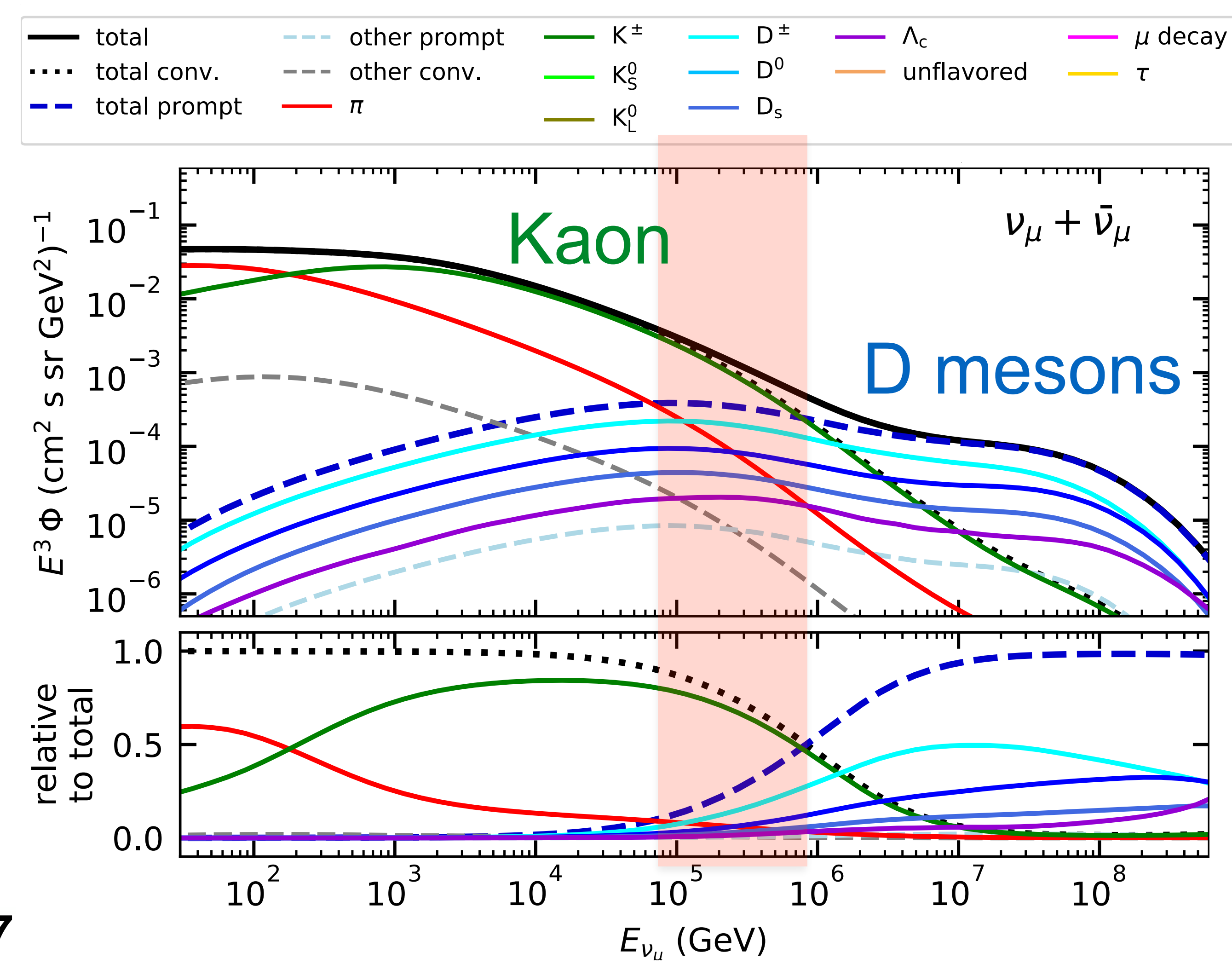


IceCube detected astronomical neutrinos.
Better understanding of background
(Atmospheric neutrinos) is required.



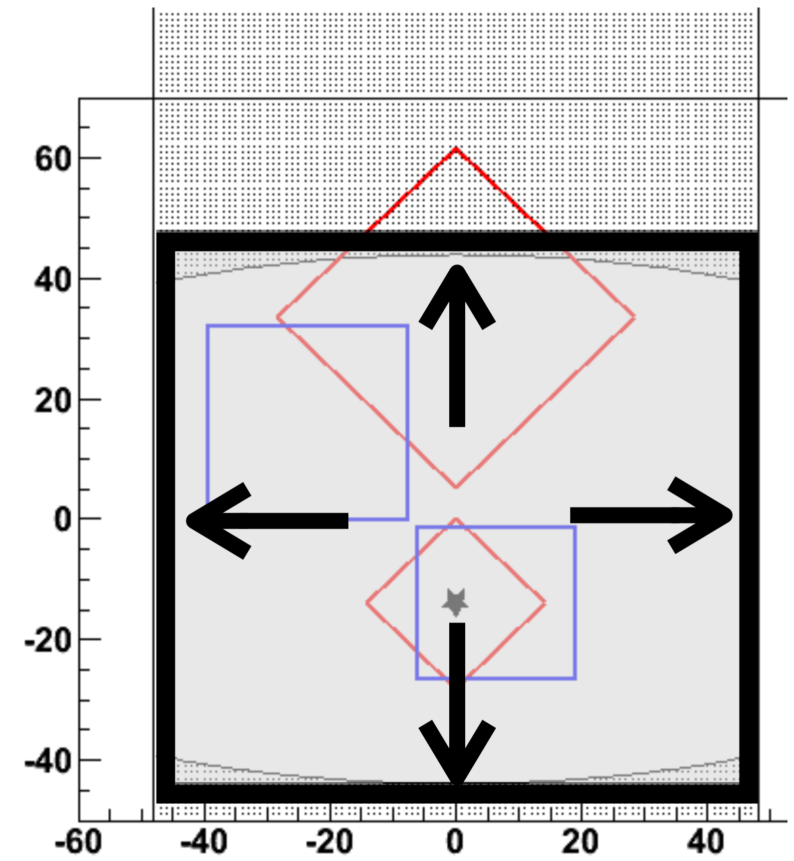
IceCube, ICRC2017

Atmospheric ν_μ flux

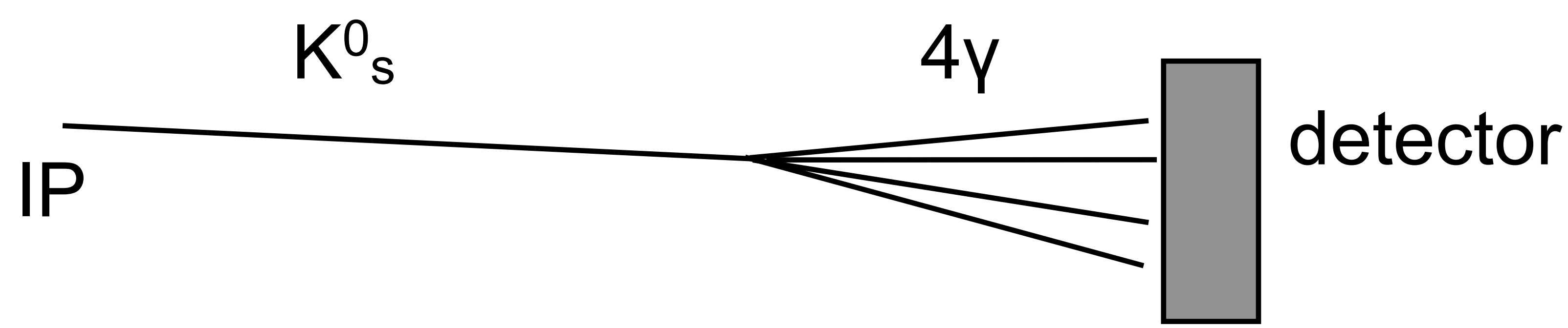


An idea for the future operation at RHIC

- *pp*,$\sqrt{s}$=510GeV scheduled in 2022.
- Key of the operation
  - High statistics of π^0 events
  - Detection of rare particles K^0, Λ



Maximize the acceptance
with keeping the performances, good energy
and position resolution for individual particles



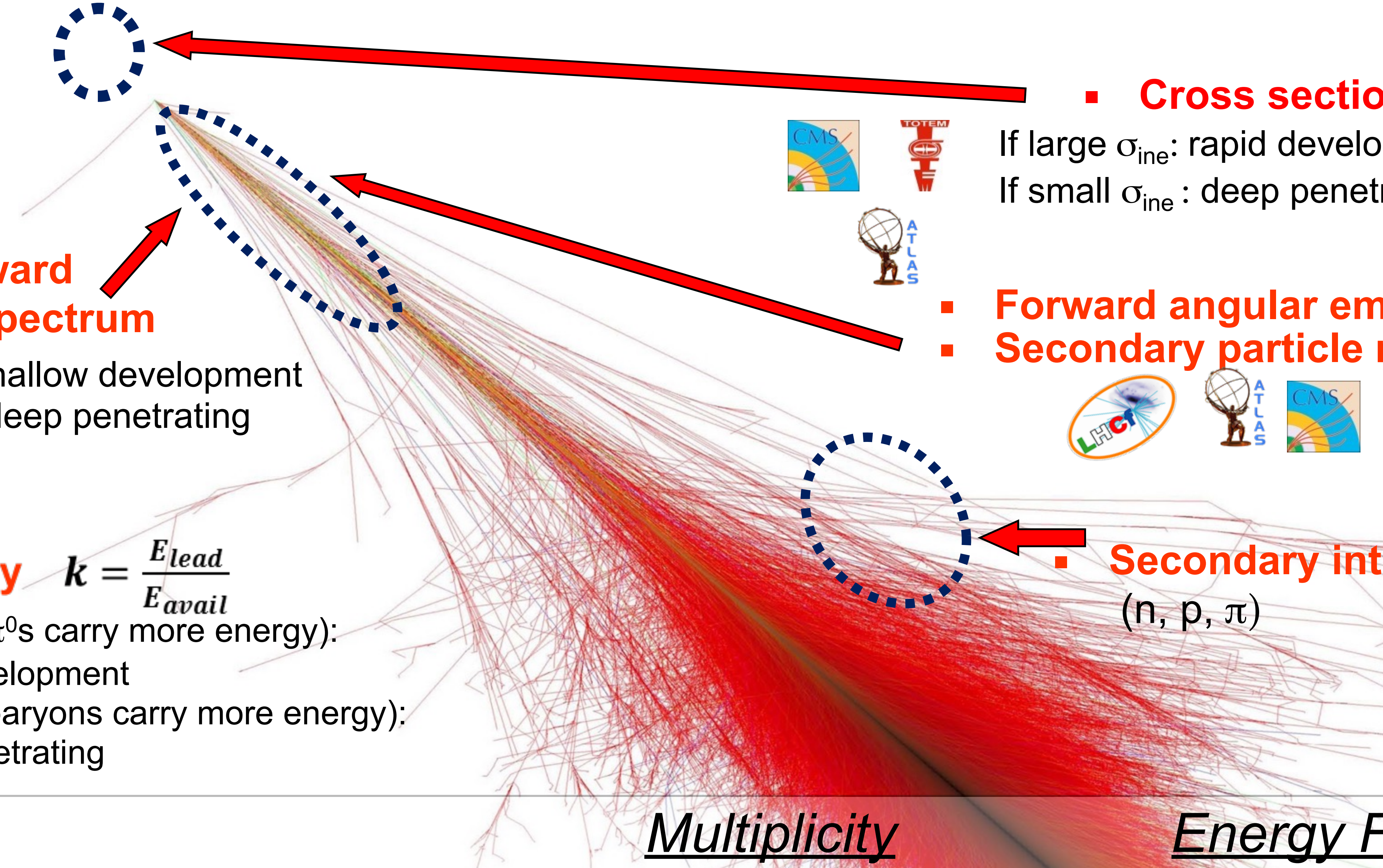
- Ideal detector: Si Pad calorimeter

Collaboration required, with ALICE-FoCal ? with future EIC-ZDC ?

Summary

- LHCf/RHICf measures the energy spectra of neutral particles, γ,π^0, and n in the very forward regions of collisions, which is important for understanding air-shower developments.
- Operations have successfully completed for
  LHCf pp: $\sqrt{s}$ = 0.9, 2.76, 7, 13 TeV and
  pPb: $\sqrt{s_{NN}}$ = 5, 8 TeV.
  RHICf pp: $\sqrt{s}$ = 510GeV (polarized beam)
- Many results were already published and many analyses are still on-going including the combined analyses with ATLAS or STAR.
- Future plan
  - Operations at LHC with pp and pO (or OO) and operation at RHIC with pp

Backup



- **Cross section**

If large σ_{ine}: rapid development

If small σ_{ine} : deep penetrating

- **Very forward energy spectrum**
  - If softer, shallow development
  - If harder, deep penetrating

- **Forward angular emission**
- **Secondary particle multiplicity**

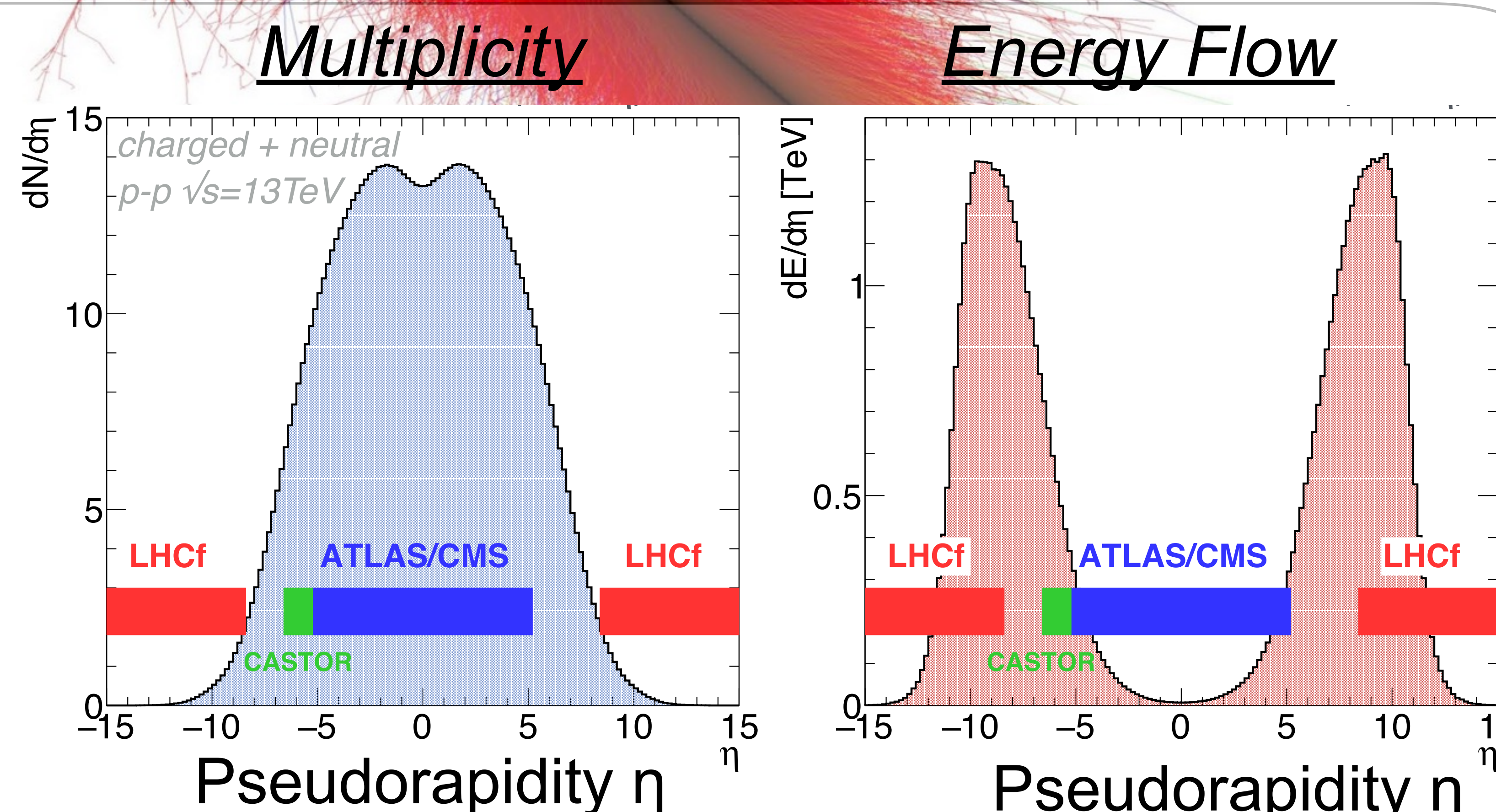
- **Elasticity** $k = \dfrac{E_{lead}}{E_{avail}}$
  - If small k (π^0s carry more energy): rapid development
  - If large k (baryons carry more energy): deep penetrating

- **Secondary interactions**

(n, p, π)

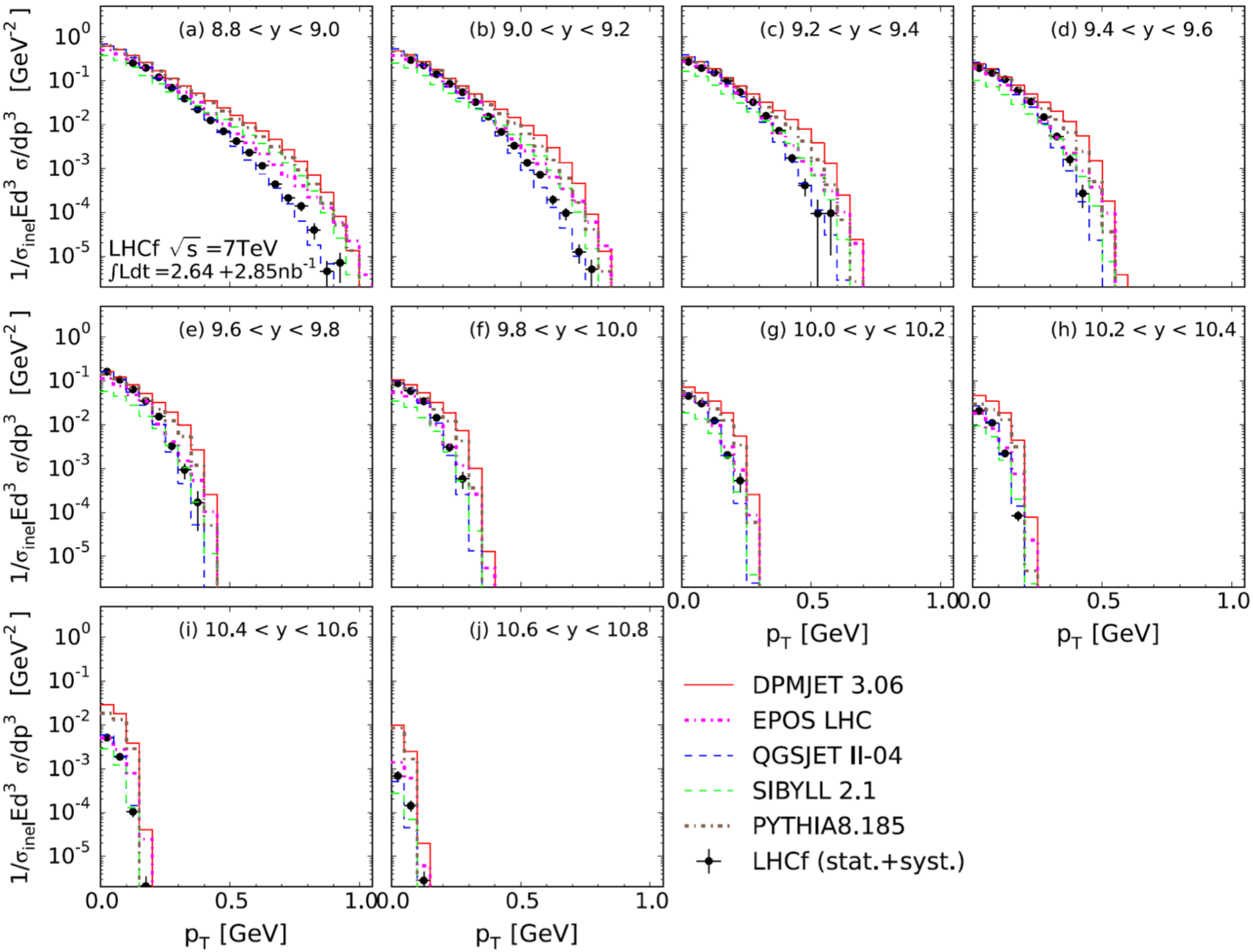
The coverage of the "wide" rapidity range by experiments is crucial

*Especially High Energy Flux in "**forward**" region*

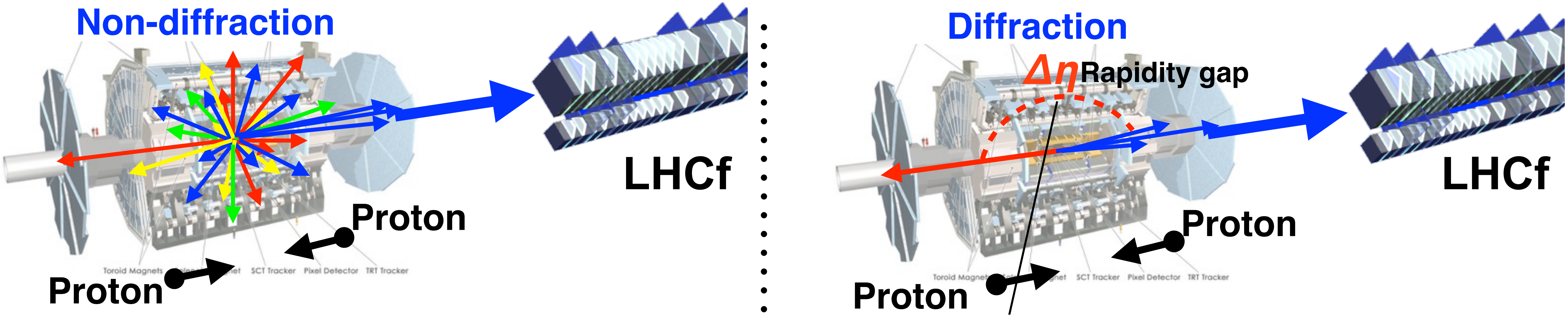


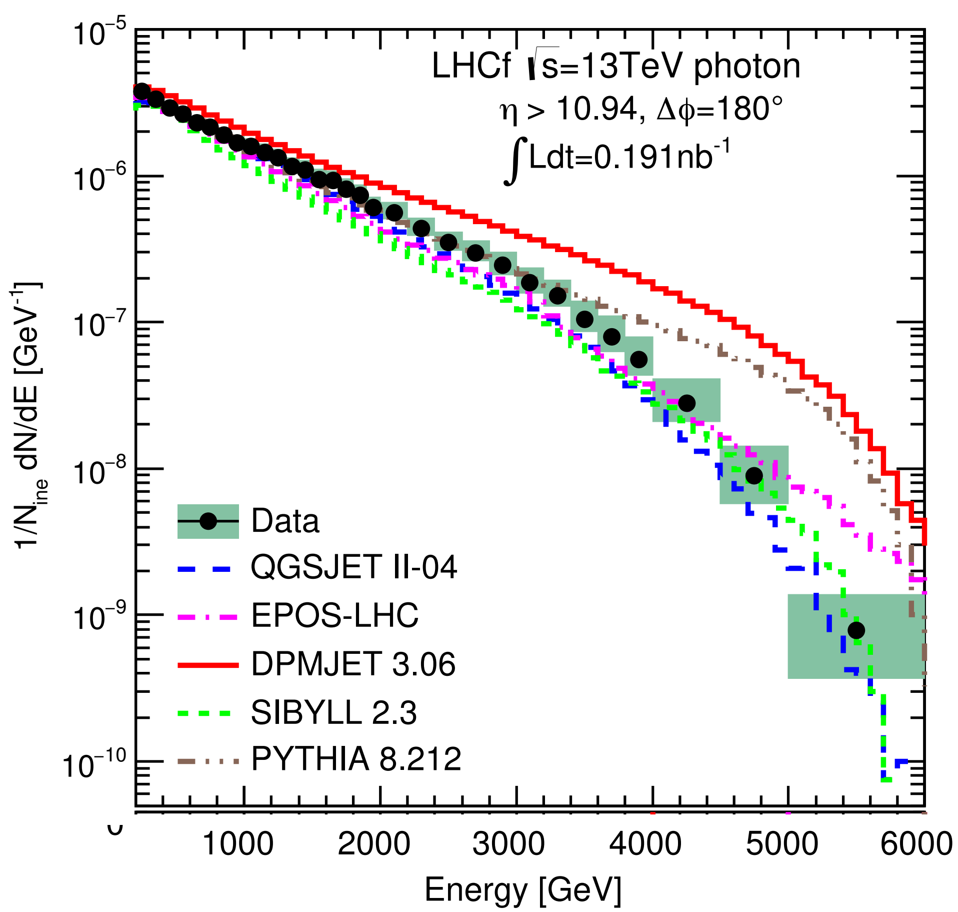
π^0 p_T spectra at pp,7TeV

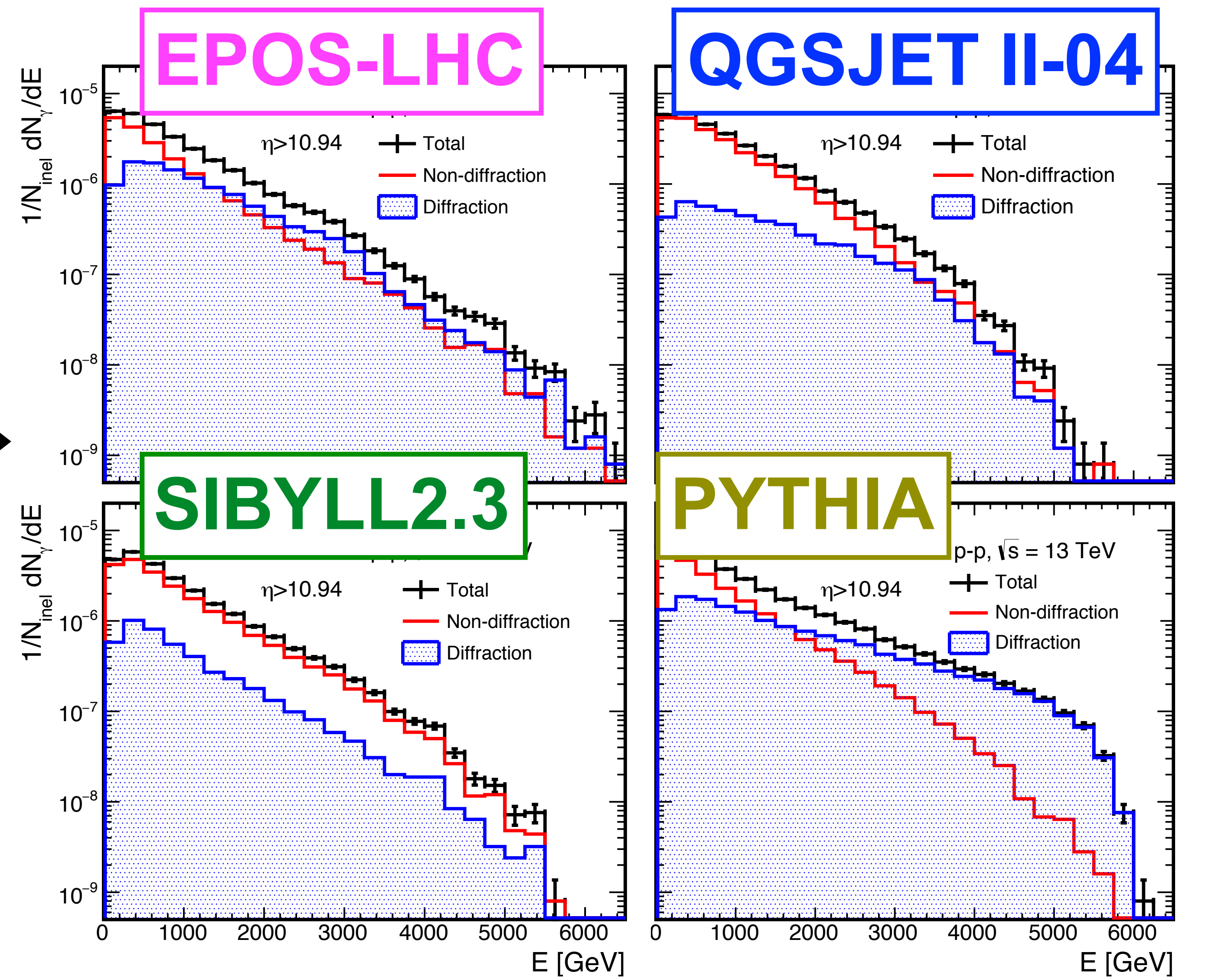
O. ADRIANI *et al.* PHYSICAL REVIEW D **94,** 032007 (2016)



Joint Analysis with ATLAS - Selection of Diffractive interactions -



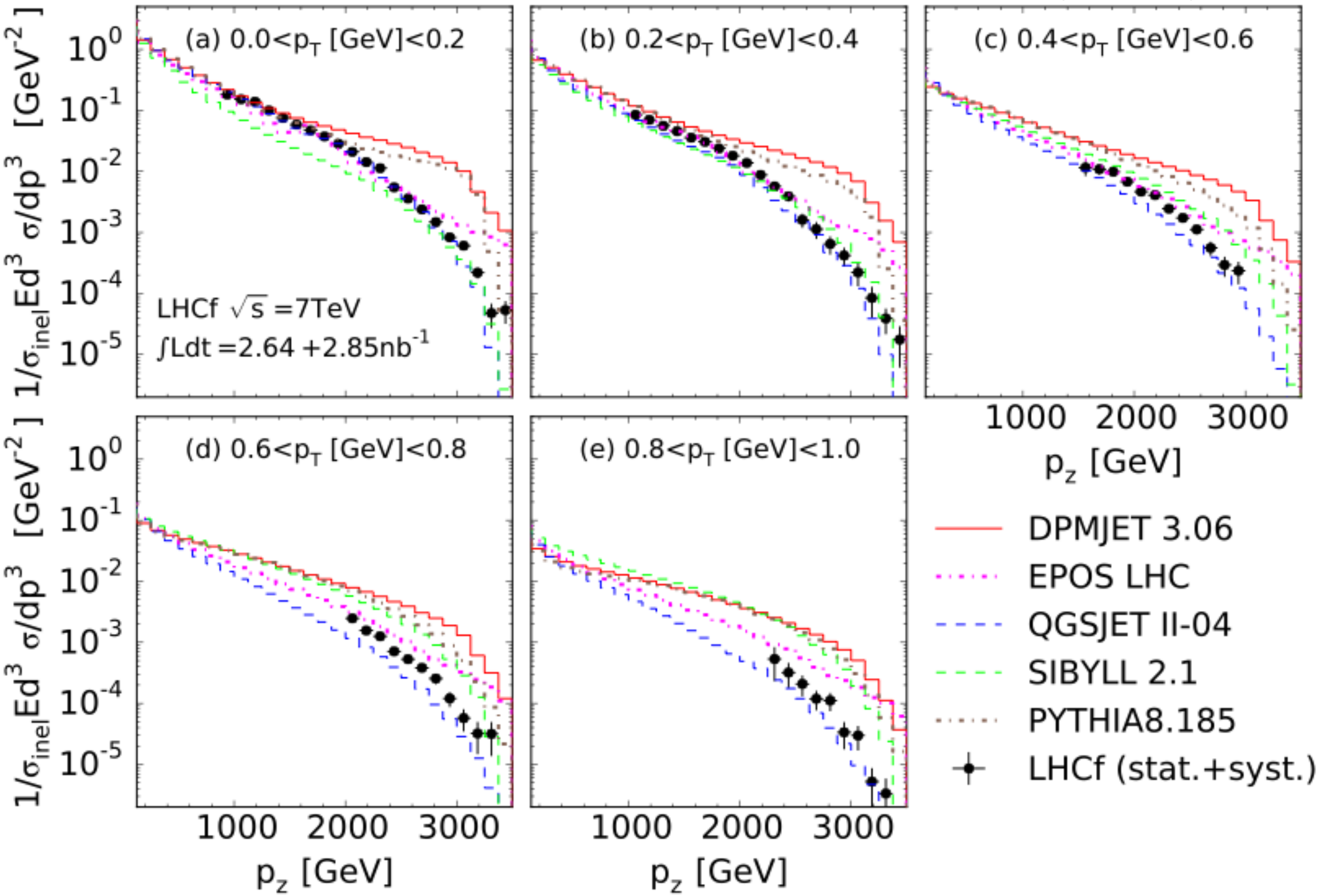




Poster by Q.Zhou; CRD131

π^0 p_Z (~E) spectra at p+p,7TeV

PRD 94 (2016) 032007

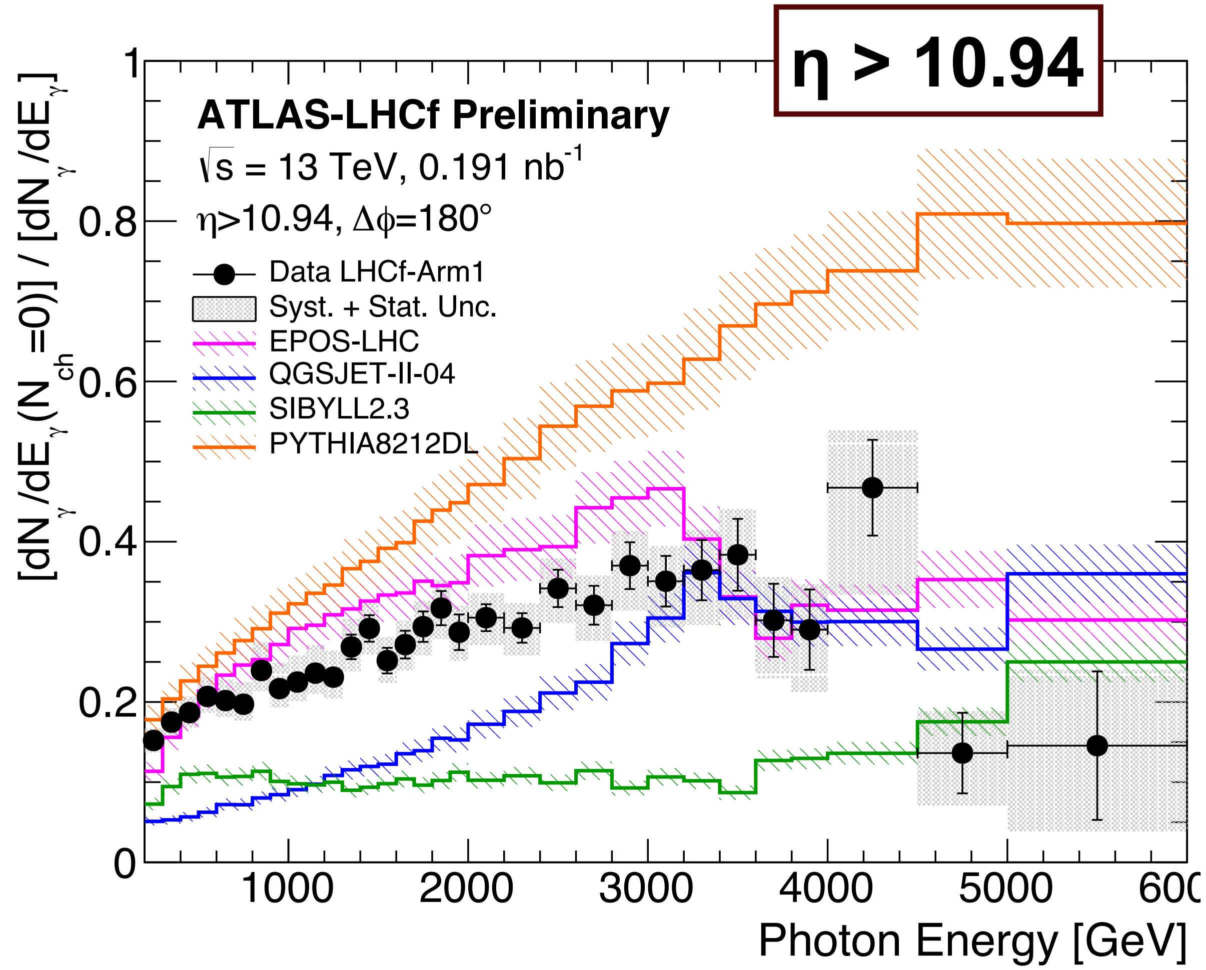


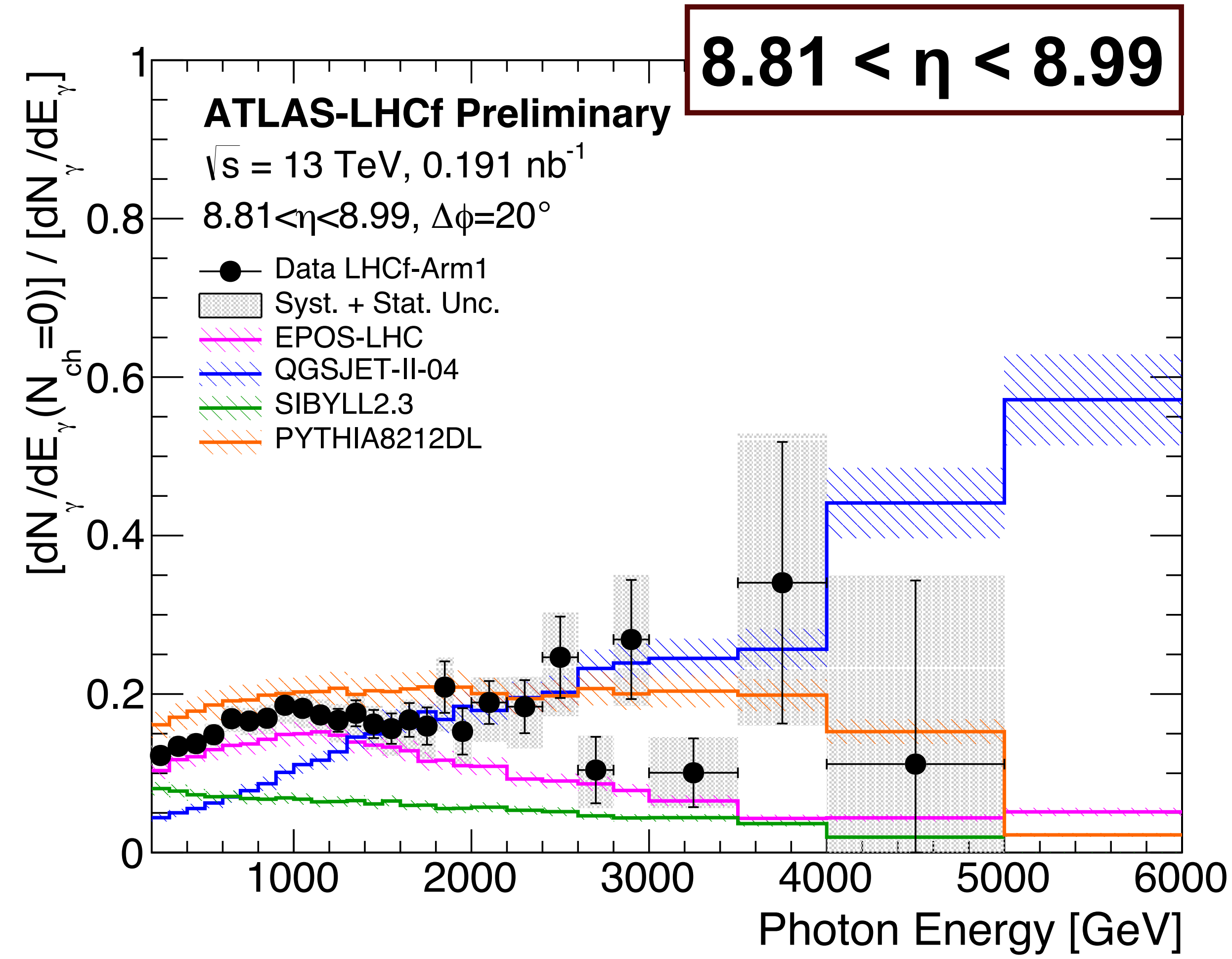
DPMJET and Pythia overestimate over all E-p_T range

Measurement of contributions of diffractive processes to forward photon spectra in *pp* collisions at √s = 13 TeV

Ratio ($N_{ch=0}$/Inclusive)

ATLAS-CONF-2017-075

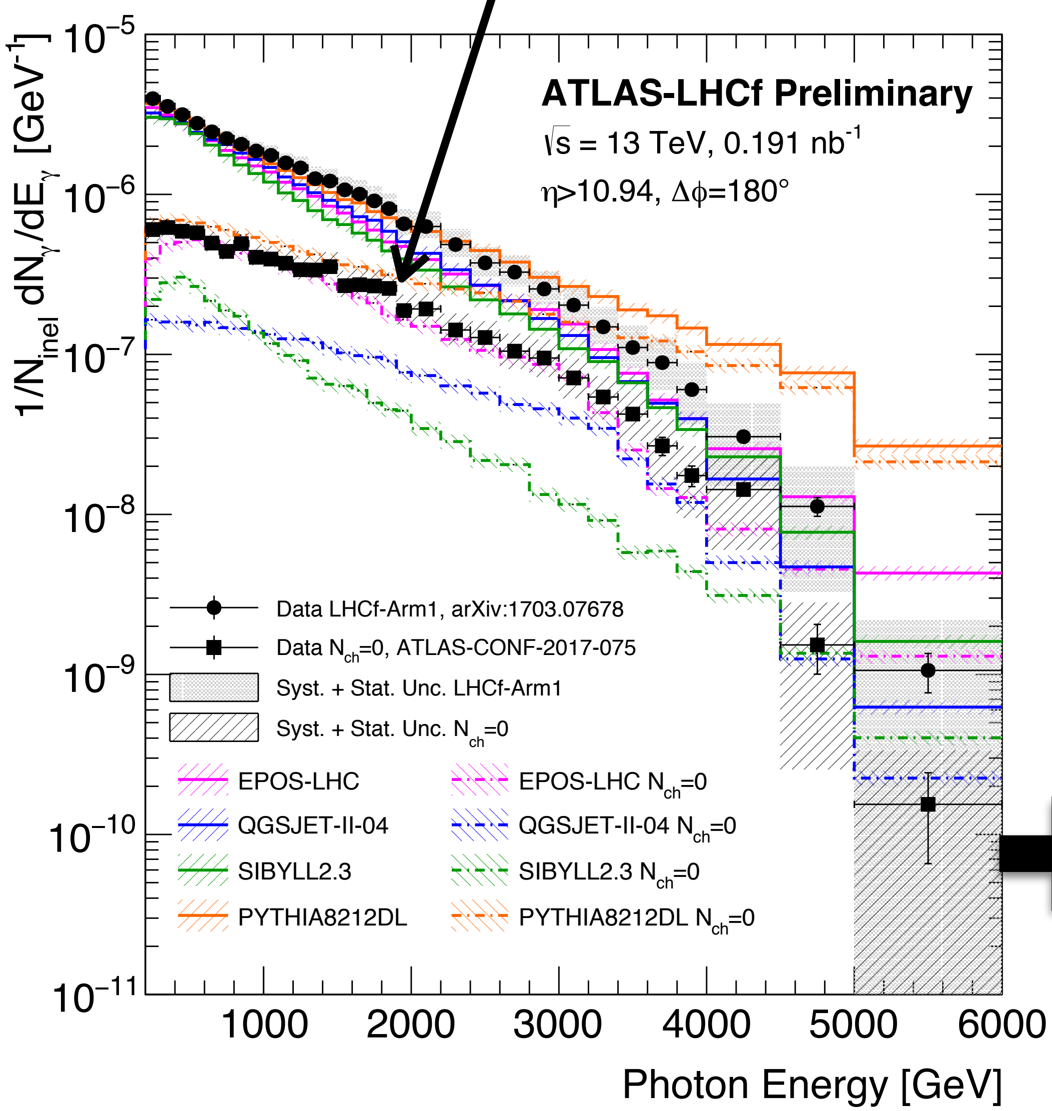




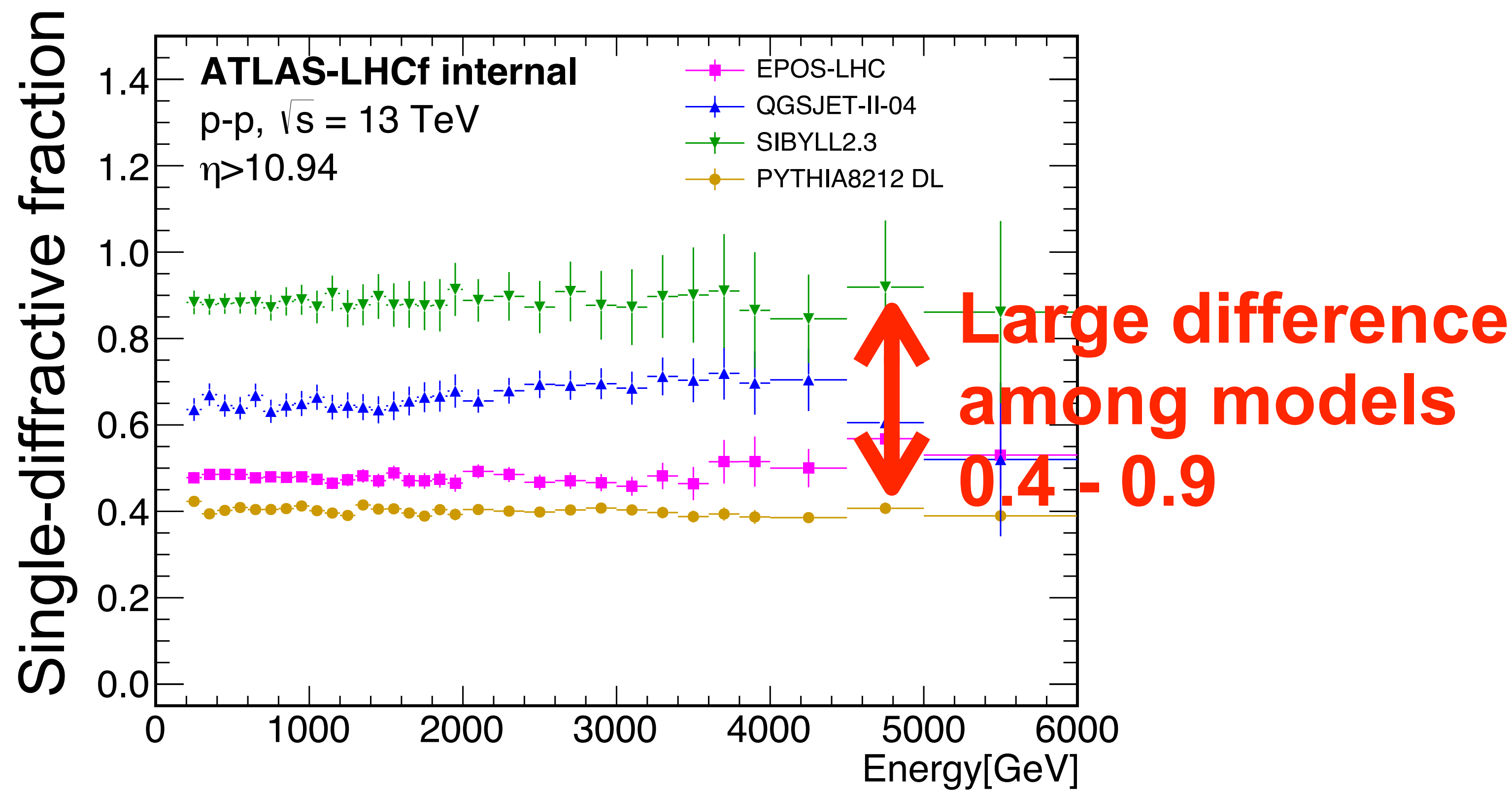
- At η>10.94, the ratio of data increased from 0.15 to 0.4. with increasing of the photon energy up to 4TeV.
- PYTHIA8212DL predicts higher fraction at higher energies.
- SIBYLL2.3 show small fraction compare with data at η>10.94.
- At 8.81 < η < 8.99, the ratio of data keep almost constant as 0.17.
- EPOS-LHC and PYTHIA8212DL show good agreement with data at 8.81 < η < 8.99.

Update plan of the joint analysis

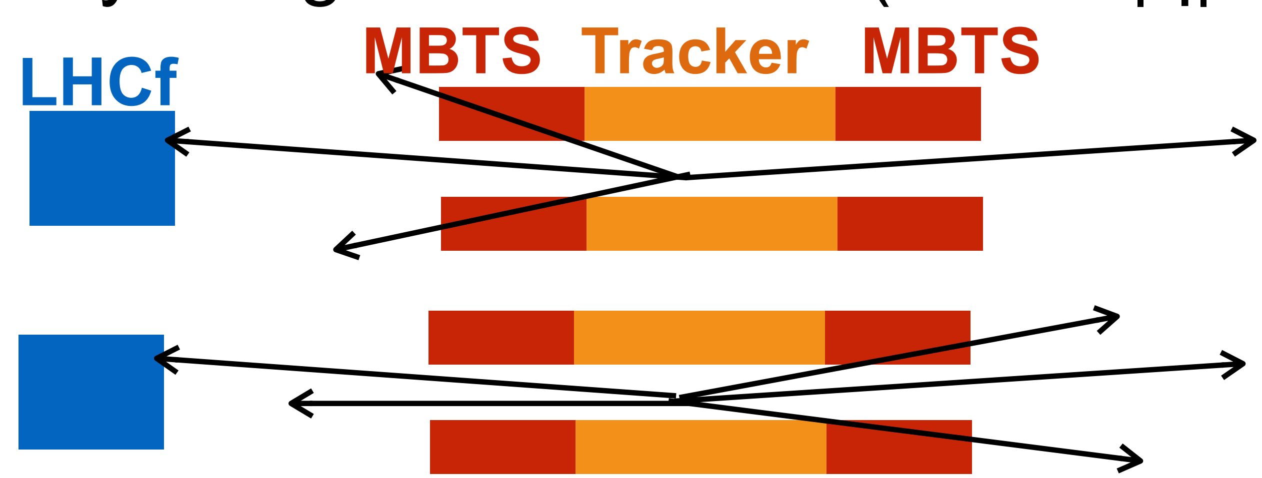
Diffractive (=Single+Double)



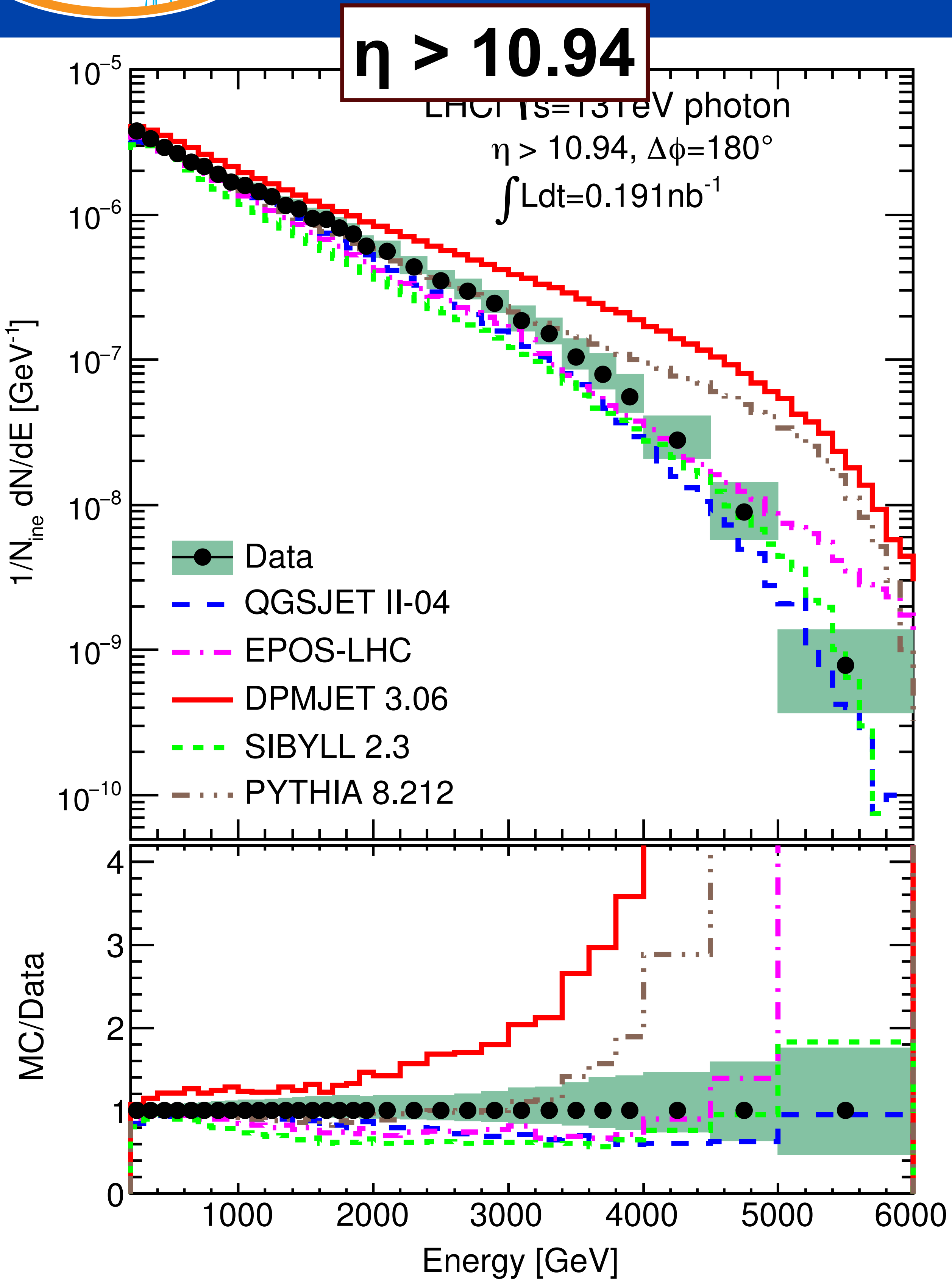
How much fraction of single diffractive in the selected events ?

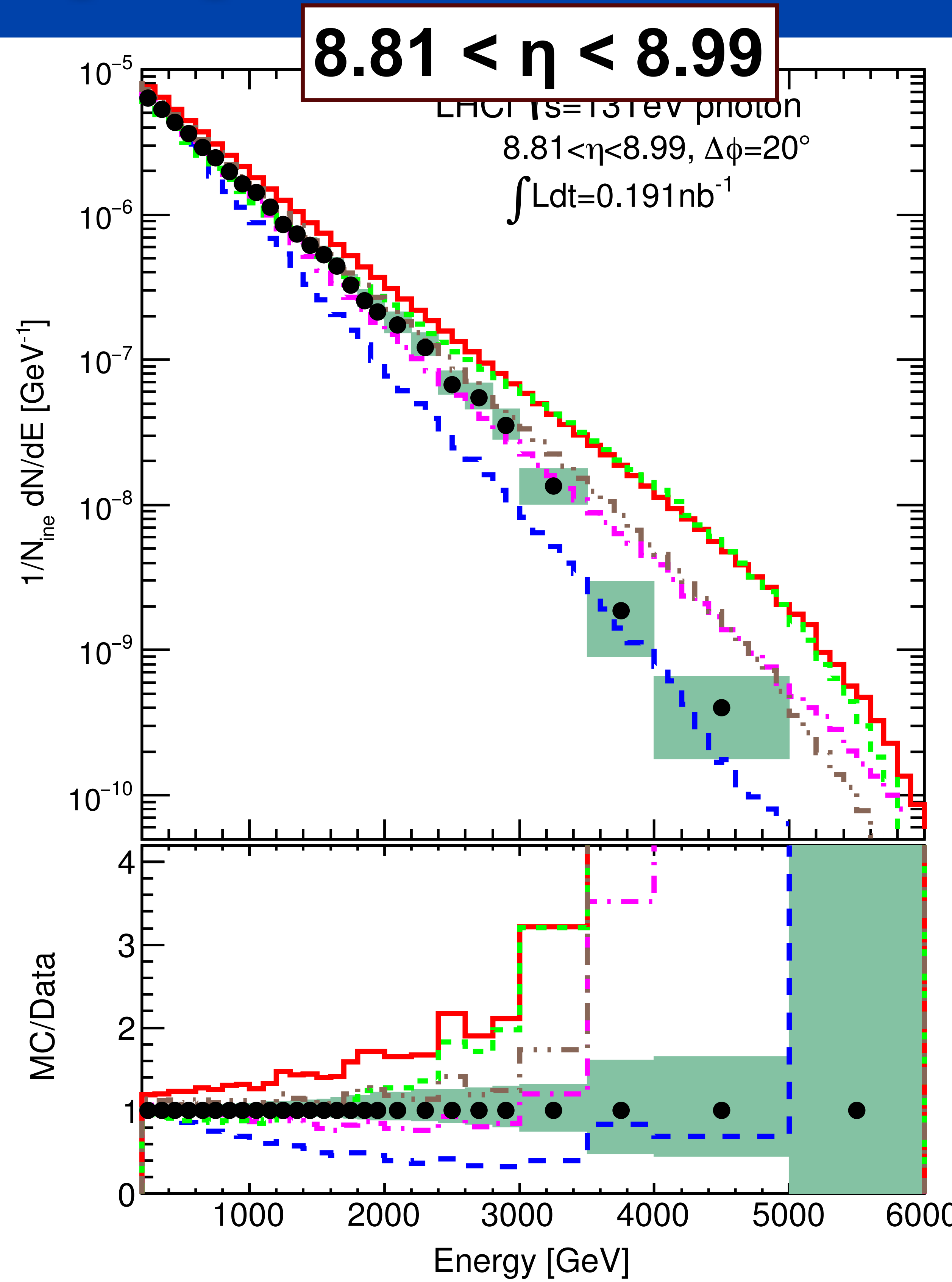


Going to measure the fraction by using ATLAS-**MBTS** (2.08 < |η| < 3.86)

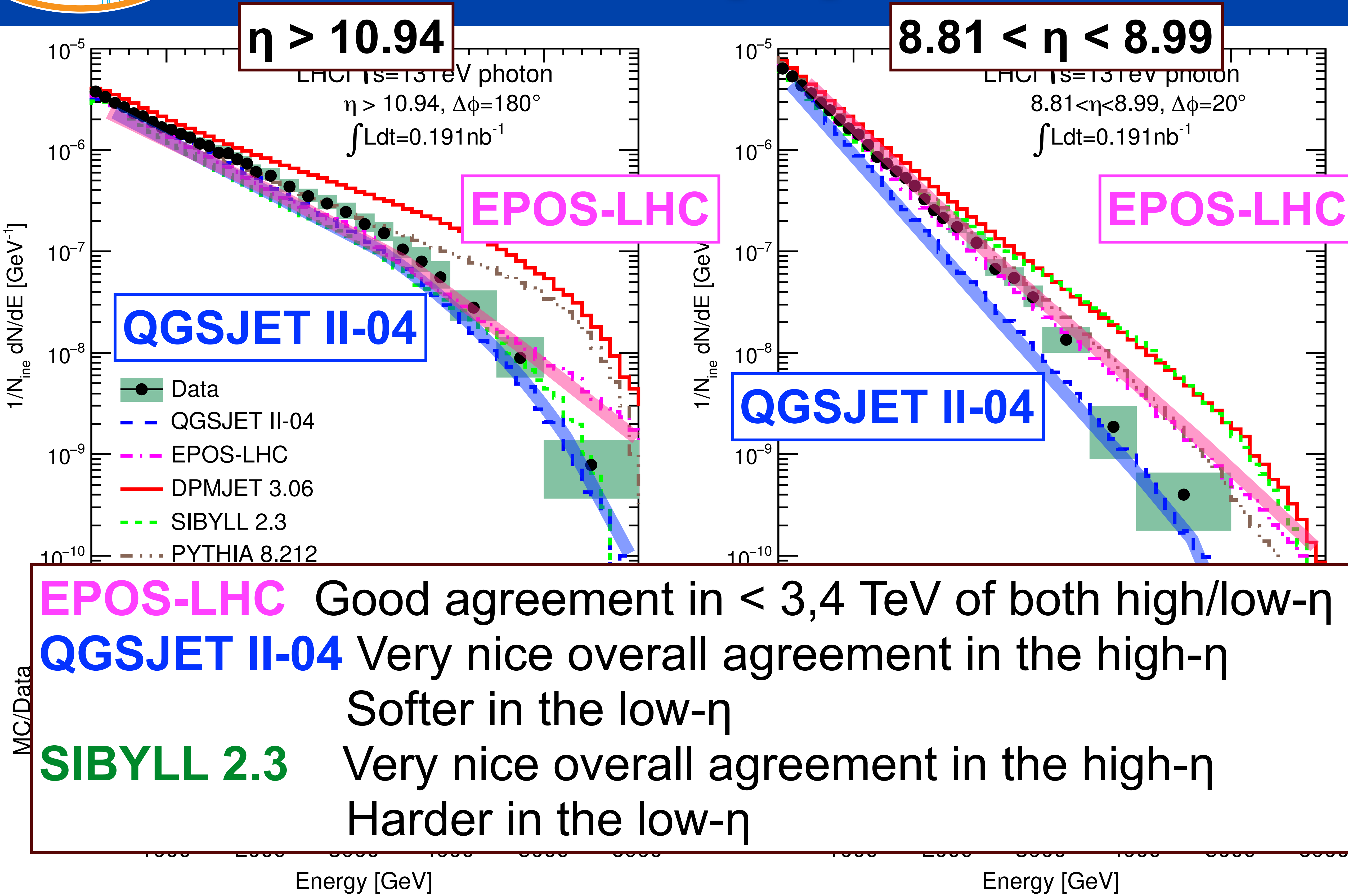


Photon at p-p, 13TeV





Photon at p-p, 13TeV



EPOS-LHC Good agreement in < 3,4 TeV of both high/low-η

QGSJET II-04 Very nice overall agreement in the high-η
Softer in the low-η

SIBYLL 2.3 Very nice overall agreement in the high-η
Harder in the low-η

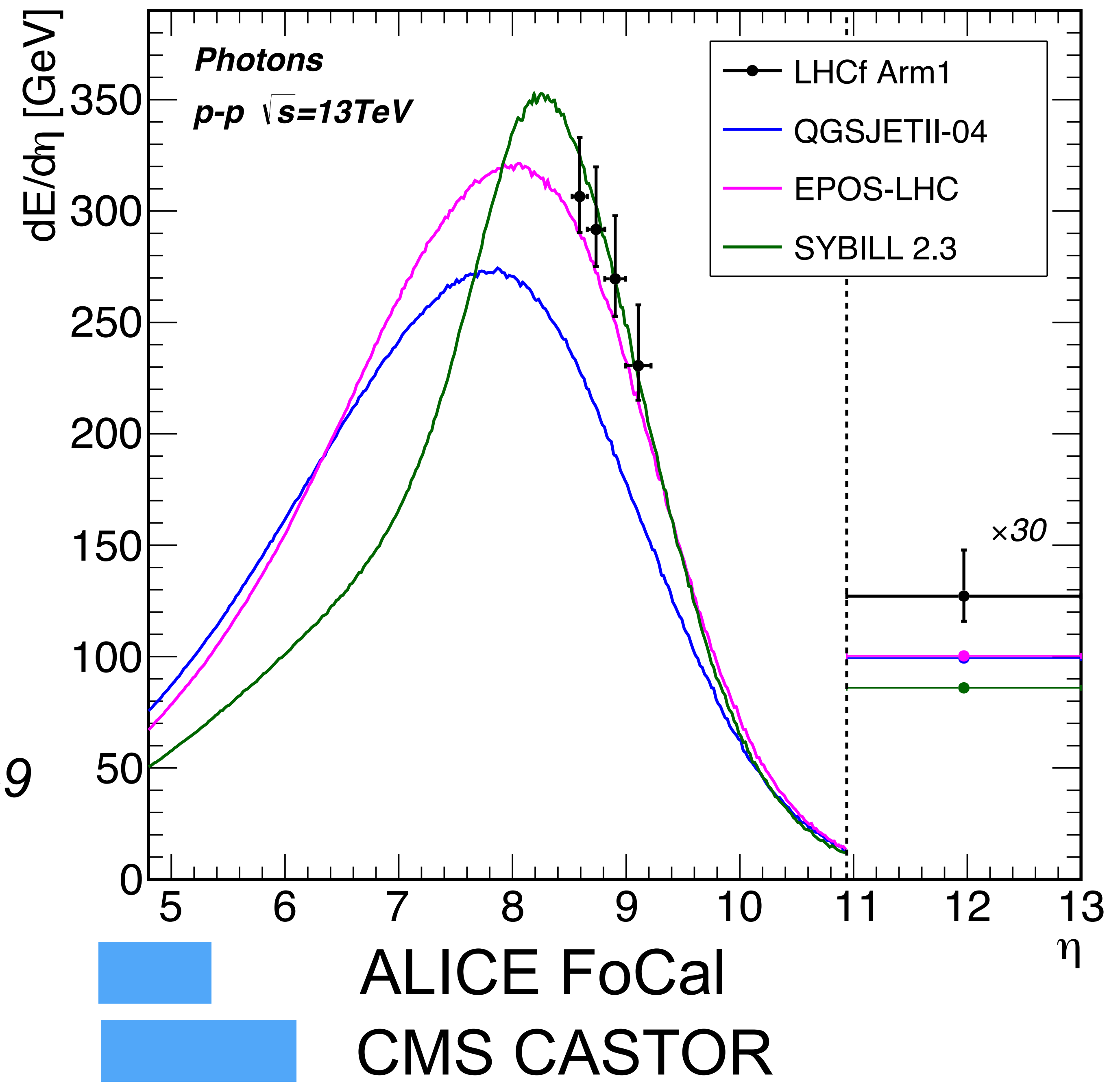
Photon Energy Flow

Energy Flow Calculation:

$$\frac{dE}{d\eta} = C_{thr}\frac{1}{\Delta\eta}\sum_{E_j>200GeV} E_j F(E_j)$$

F(Ej) : Measured differential cross-section
Δη : The pseudo-rapidity range
C_{thr} : Correction factor for the threshold 200 GeV→ 0 GeV.

Ref: Y. Makino CERN-THESIS-2017-049



EPOS-LHC, SIBYLL2.3
Good agreement
QGSJET II-04
~ 30% lower than data

Neutron, p-p $\sqrt{s}$=13TeV

Motivation

- Inelasticity measurement k_{inela}

  $k_{inela} = 1 - E_{leading}/E_{beam}$
- Large discrepancies between data and model prediction were found in the measurement at p-p, $\sqrt{s}$=7TeV

Data

- 3 hour operation in June 2015
- Low pile-up, μ~0.01

Analysis

- Particle Identification

  EM shower → develop in shallow layers

  Hadronic showers → develop in deep layers
- Energy resolution of 40%
- Contamination of Δ^0, K^0

L_{2D} (PID estimator) Distribution